Master's Thesis

A Modeling of Chroma Subsampling Artifact Assessment Metric

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Abstract

As digital broadcasting develops alongside advancements in display, video quality of broadcasting has emerged as an important issue. When the broadcasting digital signal transfers from the camera into the display TV, the optical signal changes to an electrical one before the transmittance begins. After converting to an electrical signal, the chroma subsampling, the method of compression usually used, process is implemented for compressing the digital signal. The artifact decreases the video quality, so an assessment metric is needed for increasing the video quality.

The aim of this research is to investigate the effect factors of artifact estimation with qualitative and quantitative analyses and to devise an assessment metric that can predict the 4:2:0 chroma subsampling artifact based on a psychophysical experiment.

The perceived degree of artifact was estimated by conducting a psychophysical experiment. Stimuli with a striped pattern and the 1-pixel artifact was used for estimation. Participants evaluated the magnitude of artifact in test stimuli with the reference patch, randomly shown on the monitor, having a value of 5. If the participant perceives the artifact error more than reference, they gave the value of over 5. A total of 150 test stimuli were evaluated and 10 people participated.

In the results of the experiment, 4 effect factors of artifact estimation are found: The color difference between the original and subsampled artifact, the surrounding colors effect, the neighboring colors effect, and the effect of the pixel structure. These effects help us determine the characteristics of artifact estimation. First, the color difference between the original and the subsampled artifact has the highest correlation with artifact estimation. Second, as surrounding colors have a larger difference, people underestimate the chroma subsampling error. Third, if the artifact has a similar color with one of the neighboring colors, it isn’t perceived well. The effect of pixel structure was occurred by R, G, B sub-pixel structure of LCD monitor. However, this effect factor varies depending on the pixel structure of the monitor.

Those effect factors were used to model the error assessment metric. The performance test of modeled metric was conducted with 5 participants, who were asked to select between the existing metric (dE00) and the new one modelled in this research. Most respondents selected the latter.

In a further study, the new metric can be used for evaluating chroma subsampling artifacts based on human perception. The encoding process of image and video can also be developed by applying this method, decreasing the chroma subsampling artifact.

Contents

LIST OF FIGURES

LIST OF TABLES

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1. Introduction

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1.1 Background

Since the advent of digital broadcasting, standard broadcast video has been produced according to the International Telegraph Union (ITU-R). ITU-R establishes the standards on color signals, e.g. BT.709 and BT.2020, respectively the standards for UHDTV (ITU-R, 2015) and HDTV (ITU-R, 2015). The more broadcasting technology develops, the more video resolution is needed, which entails a higher level of luminance and a wider color gamut. It also requires technology for encoding color signals and compression. Hence many researches recommend methods for encoding color signals more efficiently than current standards. One such study suggests new encoding color spaces, the ICtCp (Dolby, 2016) and Jzazbz (M Safdar and MR Luo, 2017), that mimic the human visual system. Another suggests the opto-electrical transfer function, as well as the existing function (gamma), Perceptual Quantization (PQ) function (Dolby, 2014) and Hybrid Log-Gamma (HLG) function (NHK and BBC, 2015).

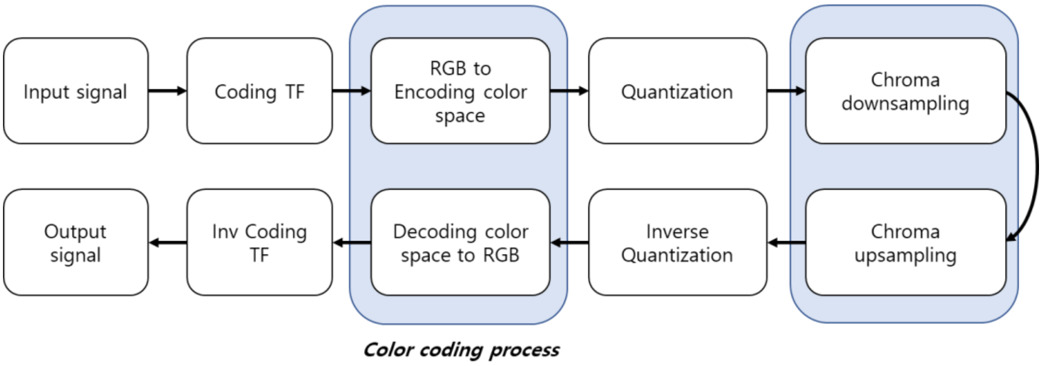

Figure 1 The simplified standard chain for coding / decoding process of video

Figure 1 represents the general process of coding and decoding video signal in broadcasting standard. First, the input linear-light RGB signal is converted into a non-linear signal a Transfer Function (TF), e.g. gamma function, PQ function. The non-linear RGB signal is then converted to the encoding color space, e.g. YCbCr, ICtCp. Finally, the chroma subsampling is implemented after quantization.

The chroma subsampling compresses the digital signal in order to reduce the image size and transfer efficiently, a method that capitalizes on a characteristic of the human visual system, namely that people have less sensitivity to chroma information than to lightness information. Before implementation of the chroma subsampling, the optical image signal is converted to the encoding color space. In this step, the signal is divided into a luma component and chroma components. Only chroma components are compressed while the luma component is maintained.

The chroma subsampling system can be expressed as J:a:b, which usually applied to 2x4 pixels, J, the number of luma samples, is usually 4; a, the number of chroma samples, is in 1st row. b refers to the number of times the chrominance changed between the 1st and 2nd row. Figure 2 represents the simple example of chroma subsampling, which are the 4:4:4, 4:2:2, and 4:2:0 methods. 4:2:0 chroma subsampling have the highest compression rate and error. According to Figure 2, 4:4:4 chroma subsampling shows the original image. Compression stands in negative proportion to chrominance information; as the former increases, the latter decreases.

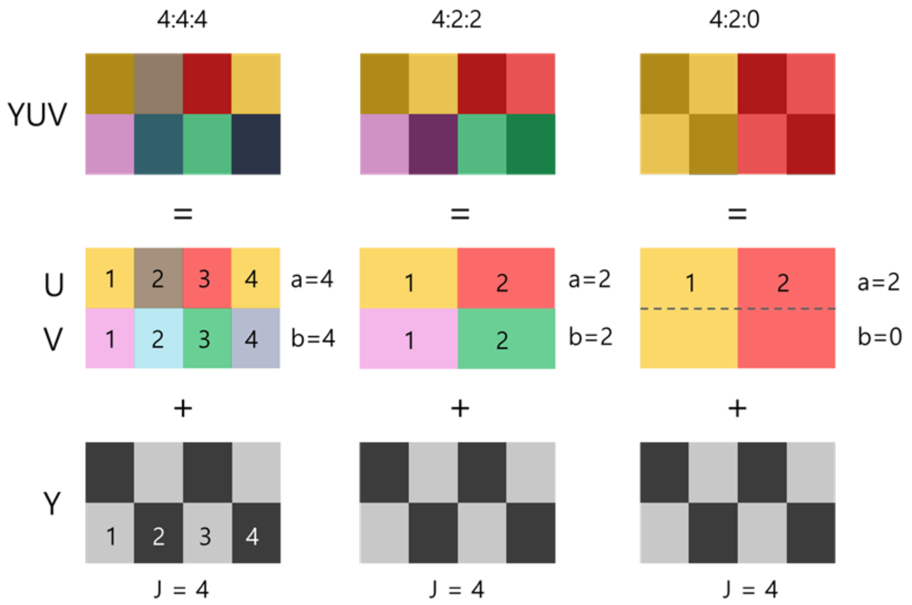

Figure 2 Method of basic chroma subsampling (4:4:4, 4:2:2, 4:2:0)

However, if luma and chroma information are not orthogonal, the chroma subsampling occurs the artifact error on the image more because the luma information changes the value depending on the chroma changing. Figure 3 provides an example of the artifact. There an artifact on the edge of the two colors, although two colors seem similar on the original image. Also, this artifact occurs more and more, as developing HDR and WCG on the broadcasting signals.

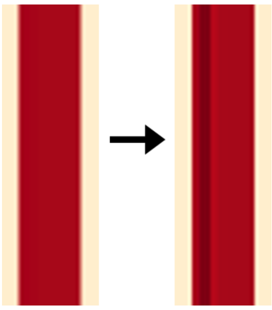

Figure 3 Example of chroma subsampling artifact

Chroma subsampling has thus emerged as an important issue. Usually, 4:2:0 chroma subsampling is used for standards, but it has the highest compression rate and error. Thus, it is needed to predict the error produced by chroma subsampling for developing a low error transferring method.

There are some metrics to evaluating the image error, most of metrics evaluate the image with lightness, not chroma. Also, they fail to reflect the human color perception of the artifact. Thus, the metric was developed based on psychophysical experimental data in this research.

1.2 Aim of the Research

The aim of this research is to make the 4:2:0 chroma subsampling error assessment metric based on the human color perception. The aim of this research can be divided into three.

1) To collect the artifact estimation data by using psychophysics experiment

2) Quantitative and qualitative analysis of the 4:2:0 chroma subsampling artifact perception.

3) Modeling as a metric for assessment images based on the analysis.

1.3 Thesis Outline

To make the 4:2:0 chroma subsampling error assessment metric, we conducted a psychophysical experiment by using the stimuli having the artifact. The psychophysical experiment method was a magnitude estimation with reference. Participants evaluated the error of how much they can see.

The results were compared to a various color errors on each stimulus. The experimental data were analyzed for modeling. By using results helped us identify three modelling criteria of modeling. The first was for baseline data, and the second and third were about surrounding conditions. After finishing the modeling, the applied example was compared with CIEDE00.

Chapter 2 briefly introduces the literature survey in terms of basic color science (e.g. color appearance terminology, color appearance model, and color difference equations). Moreover, the encoding color space is described about encoding color space, the process of coding / decoding light signal into the digital signals.

In the chapter 3, the experimental design is introduced. The environment and instruments used for the experiment, the monitor characterization, and test stimuli and color are introduced. Also, procedure of experiment and analysis method are explained.

In the chapter 4, the effect factors of artifact estimation are described. There are 4 effect factors found based on psychophysical experimental results: 1) The effect of color difference between original colors and subsampled colors, 2) The effect of surrounding colors, 3) The effect of neighboring colors and 4) The effect of pixel structure.

In chapter 5, the process of metric modeling is described step by step. The effect factors of artifact estimation are applied for modeling.

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2. Literature Survey

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2.1 CIE Colorimetry

2.1.1 CIE Standard Observer

When the observer perceives the object, the color perception is different depending on the observers because of the different sensitivities of cone cells. To standardize the color appearance, the CIE defines a standard observer, representing the chromatic sensitivity of the human eye. The sensitivity curve was defined by using the trichromatic color matching experiment in 1931.

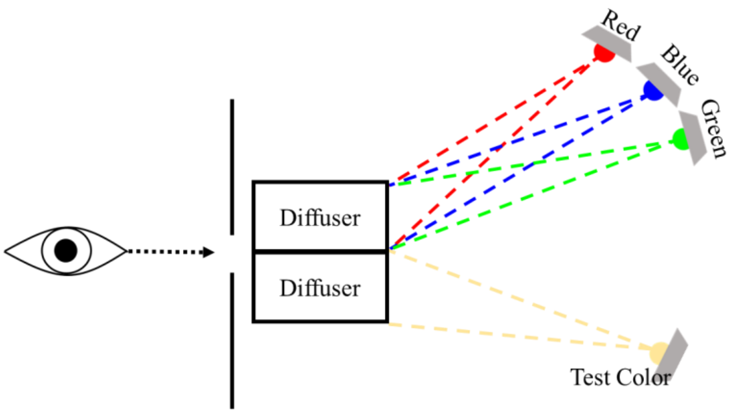

Figure 4 Experimental setting of color-matching

Figure 4 represents the basics of the trichromatic color-matching experiment. The test colors were matched with hue, colorfulness, and brightness by adjusting three monochromatic light. By using the trichromatic color matching experiment data, the 2º standard observer was standardized and in 1963, CIE also recommended another supplementary standard observer which has the field of view 10º.

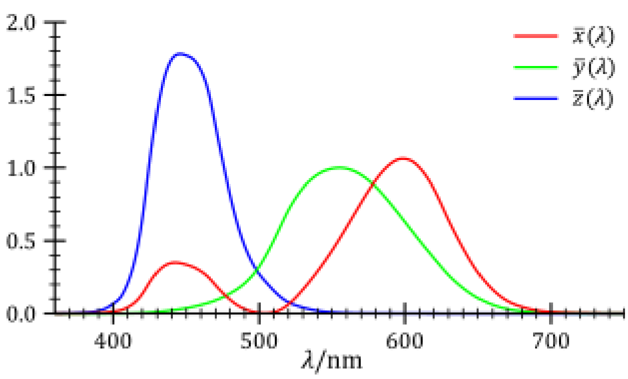

Figure 5 Color matching function of CIE standard observer 1931 (2°)

2.1.2 CIE XYZ Tristimulus Values

When judging the color of the object, three components are needed for color perception: light source, object, and observer. It means that the color can be quantified with spectral power distribution for the light source, spectral reflectance for the object, and color matching function from the observer, usually using standard colorimetric observer. X, Y, Z tristimulus values can be calculated by

$$X = k \int S(\boldsymbol{\lambda}) R(\boldsymbol{\lambda}) \bar{x}(\boldsymbol{\lambda}) d(\boldsymbol{\lambda})$$

$$Y = k \int S(\boldsymbol{\lambda}) R(\boldsymbol{\lambda}) \bar{y}(\boldsymbol{\lambda}) d(\boldsymbol{\lambda})$$

$$Z = k \int S(\boldsymbol{\lambda}) R(\boldsymbol{\lambda}) \bar{z}(\boldsymbol{\lambda}) d(\boldsymbol{\lambda}),$$

, where $S(\lambda)$ means the spectral power distribution, $R(\lambda)$ means the spectral reflectance for object and $\bar{x}(\boldsymbol{\lambda})$, $\bar{y}(\boldsymbol{\lambda})$ and $\bar{z}(\boldsymbol{\lambda})$ are color matching function.

Y is the luminance value from 0 to 100, Z is quasi-equal to blue, or S cone response, and X is the combined result of the response.

2.1.3 Chromaticity

Colors which human can perceive can be quantified in three-dimensions with CIE Tristimulus value. Also, the color can be expressed by 2-dimension with chromaticity. It means that the concept of color can be divided into two parts: brightness and chromaticity. It makes the color into 2-dimensional data. The chromaticity is derived by the two parameters x and y using X, Y, and Z tristimulus values,

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

Figure 6 shows the chromaticity diagram with small x and y. The boundary of the locus is spectral data with wavelength. It usually used to represent the color gamut.

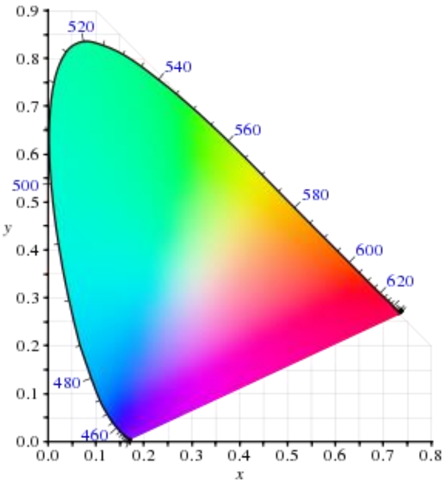

Figure 6 The CIE 1931 chromaticity diagram.

2.2 Color Appearance Model

2.2.1 Color Appearance Terminology

The color appearance attributes were defined in International Lighting Vocabulary by CIE (CIE, 1987, 2011a; Hunt & Pointer, 2011; M. D. Fairchild, 2013)

Brightness

Brightness is defined as the attribute of a visual perception according to which an area appears to exhibit more or less light. (Adjectives: *bright* and *dim*.)

Hue

Hue is defined as the attribute of a visual perception according to which an area appears to be similar to one, or ~~to~~ proportions of two, of the perceived colors red, yellow, green, and blue.

Colorfulness

Colorfulness is defined as the attribute of a visual perception according to which an area appears to exhibit more or less of its hue.

Lightness

Lightness is used to describe the brightness of area relative to that of a similarly illuminated white. Lightness is defined as the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Lightness can be expressed by

$$\text{Lightness} = \frac{Brightness}{Brightness\ of\ White}$$

Chroma

Chroma is defined as the colorfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Chroma can be expressed by

$$\text{Chroma} = \frac{Colorfulness}{Brightness\ of\ White}$$

2.2.2 CIELAB

The CIELAB color space is defined by CIE(International Commission on Illumination) in 1976. This can be expressed for tristimulus values which are normalized to the white.

$$L* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16$$

$$a* = 500\left(\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right)$$

$$b* = 500\left(\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right)$$

$$C*_{ab} = \sqrt{a*^2 + b*^2}$$

$$h_{ab} = \tan^{-1}\left(\frac{b*}{a*}\right)$$

In the equations, the X, Y, and Z are the tristimulus values of target color, and X_n, Y_n, and Z_n are the tristimulus values of the reference white. L* represents the lightness [0,100], a* is redness (+) - greenness (-), b* is yellowness (+) - blueness (-). By using a* and b*, the chroma and hue also can be calculated.

2.2.3 CIECAM02

The CIE has endorsed CIECAM02 which is a development of the earlier model CIECAM97s and CAM97u which is the developed version for unrelated colors, and CAM97c which is for comprehensive use (Luo & Hunt, 1998; Li, Luo & Hunt, 2000; M. D. Fairchild, 2001; Hunt, C. J. L, L. Y. Juan & Luo 2002; Moroney, M. D. Fairchild, Hunt, Li, Luo, & Newman, 2002). The first step in CIECAM02 is a chromatic adaptation. Before starting the chromatic adaptation, the input data should be set. The input data for the CIECAM02 include the relative tristimulus values of the test stimulus and the reference white point. The adapting luminance LA, the relative luminance of the surround (dark, dim, average), depending on the surround condition, the c, Nc and F parameters will be changed like table 1. c is an exponential nonlinearity, Nc is the chromatic induction factor, and F is the maximum degree of adaptation. Background luminance factor Yb and background parameters Ncb and Nbb are also needed.

Table 1 Parameters table of CIECAM02

Viewing condition	c	Nc	F
Average surround	0.69	1.0	1.0
Dim surround	0.59	0.9	0.9
Dark surround	0.525	0.8	0.8

Step 1. Chromatic Adaptation

$$D = F \cdot \left[1 - \frac{1}{3.6} \cdot e^{\frac{-L_A - 42}{92}}\right],$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \ M_{CAT02} = \begin{bmatrix} 0.7329 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

$$R_C = \left[D \cdot \left(\frac{R_{WR}}{R_W} + 1 - D\right)\right] \cdot R, \ G_C = \left[D \cdot \left(\frac{G_{WR}}{G_W} + 1 - D\right)\right] \cdot G, \ B_C = \left[D \cdot \left(\frac{B_{WR}}{B_W} + 1 - D\right)\right] \cdot B$$

$$D = F \cdot \left[1 - \frac{1}{3.6} \cdot e^{\frac{-L_A - 42}{92}}\right],$$

$$\begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} = M_{CAT02}^{-1} \cdot \begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix},$$

Step 2. Dynamic Adaptation

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_{HPE} \cdot \begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix}, \; M_{HPE} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.0000 \end{bmatrix}$$

$$R'_a = 400 \frac{(F_L R'/100)^{0.42}}{(F_L R'/100)^{0.42} + 27.30} + 0.1$$

$$G'_a = 400 \frac{(F_L G'/100)^{0.42}}{(F_L G'/100)^{0.42} + 27.30} + 0.1$$

$$B'_a = 400 \frac{(F_L B'/100)^{0.42}}{(F_L B'/100)^{0.42} + 27.30} + 0.1 \;,$$

,where $F_L = 0.2 \cdot k^4 \cdot (5L_A) + 0.1 \cdot (1 - k^4)^2 \cdot 5{L_A}^{1/3}$, $k = 1/(5L_A + 1)$.

Step 3. Opponent Color Signals

Achromatic signal $A = [2 \cdot R'_a + G'_a + 0.05 \cdot B'_a - 0.305] \cdot N_{bb}$, $N_{bb} = \frac{0.725}{n^{0.2}}$, $n = \frac{Y_b}{Y_w}$

$$Redness - Greenness\ signal \qquad a = R'_a - \frac{12}{11} \cdot G'_a + \frac{1}{11} \cdot B'_a$$

$$Yellowness - Blueness\ signal \qquad b = \frac{1}{9}(R'_a + G'_a - 2 \cdot B'_a)$$

Step 4. Color Appearance Predictors

(Achromatic Predictors : Lightness J, Brightness Q)

$$J = 100 \cdot \left(\frac{A}{A_W}\right)^{c \cdot z}, z = 1.48 + \left(\frac{Y_b}{Y_W}\right)^{0.5}$$

$$Q = \frac{4}{c} \cdot \sqrt{\frac{J}{100}} (A_w + 4) \cdot {F_L}^{0.25}$$

(Hue Predictors)

$$h = \tan^{-1}\left(\frac{b}{a}\right) \text{ (degree)}$$

$$H = H_i + \frac{100 \cdot \frac{h' - h_i}{e_i}}{\frac{h' - h_i}{e_i} + \frac{h_{i+1} - h'}{e_{i+1}}}$$

Table 2 Hue angle (h) and Eccentricity (e) of unique hue

Unique Hue	Red	Yellow	Green	Blue
Hue angle h	20.14	90.0	164.25	237.53
Eccentricity e	0.8	0.7	1.0	1.2

(Chromatic Predictors: Chroma C, Colorfulness M, Saturation s)

$$C = t^{0.9} \cdot \sqrt{\frac{J}{100}} \cdot (1.64 - 0.29^{n})^{0.73}$$

, where $t = \frac{\left(\frac{50000}{13} \cdot N_c \cdot N_{cb}\right) \cdot e_t \cdot (a^2 + b^2)^{1/2}}{R_a + G_a + \left(\frac{21}{20}\right) \cdot B_a}$, $N_{cb} = 0.725 \cdot \left(\frac{Y_w}{Y_b}\right)^{0.2}$,

$$M = C \cdot {F_L}^{0.25}$$

$$s = 100 \cdot \left(\frac{M}{Q}\right)^{0.5}$$

2.3 CIE Color Difference

2.3.1 CIELAB dE*$_{ab}$

The color difference of CIELAB color space is measured by the Euclidean distance between two colors. It can be expressed with lightness, chroma and hue differences also.

$$\Delta L* = L*_2 - L*_1$$

$$\Delta a* = a*_2 - a*_1$$

$$\Delta b* = b*_2 - b*_1$$

$$\Delta C*_{ab} = C*_2 - C*_1,$$

The color difference equations can be expressed by two equations:

$$\Delta E*_{ab} = \sqrt{\Delta L*^2 + \Delta a*^2 + \Delta b*^2}$$

$$\Delta E*_{ab} = \sqrt{\Delta L*^2 + \Delta C*_{ab}{}^2 + \Delta H*_{ab}{}^2}$$

So, the hue difference can be calculated by the following equation:

$$\Delta H*_{ab} = \sqrt{\Delta E*_{ab}{}^2 - \Delta L*^2 - \Delta C*_{ab}{}^2}$$

2.3.2 CIEDE2000

The CIE suggested the color difference equation, CIE94 in 1994. After then, CIEDE2000 which solves the perceptual uniformity issue adding five corrections in CIE94 (ISO/CIE, 2014; Luo, Cui & Rigg, 2001). The blue region problem was dealing with the hue rotation term (R_T) and the compensation for neutral colors, lightness (S_L), chroma (S_C) and hue (S_H). The equation of CIEDE2000 is the following below.

$$\Delta E*_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}}, \text{ where L' = L*}$$

$$\Delta L' = L'_2 - L'_1$$

$$\Delta C' = C'_2 - C'_1$$

$$\Delta H' = 2\sqrt{C'_2 \cdot C'_1}\sin\left(\frac{\Delta h'}{2}\right)$$

$$\Delta h' = h'_2 - h'_1$$

The subscripts 1 and 2 means the reference color and test colors.

The weighting factor of CIEDE2000 can be calculated by

$$S_L = 1 + \frac{0.015(\overline{L'} - 50)^2}{\sqrt{20 + (\overline{L'} - 50)^2}}$$

$$S_C = 1 + 0.045\overline{C'}$$

$$S_H = 1 + 0.015\overline{C'} \cdot T,$$

, where $T = 1 - 0.17\cos(\overline{h'} - 30°) + 0.24\cos(3\overline{h'} + 6°) - 0.20\cos(4\overline{h'} + 63°)$.

The rotation term R_T is as follows:

$$R_T = -\sin(2\Delta\theta) \cdot R_C \ ,$$

where $\Delta\theta = 30exp\left(-\left(\frac{\overline{h\prime} - 275°}{25}\right)^2\right)$ and $R_C = 2\sqrt{\frac{\overline{C\prime}^7}{\overline{C\prime}^7 + 25^7}}$.

2.4 Encoding Color Space

The encoding color space is the color-coding process of the video signal. The color-coding is the process of converting the linear-light signal into an electrical signal (digital signal) when the image signal is transferred to the TV. To convert the signal, the transfer function and conversion equations are needed, and the color-coding standard has been followed nowadays. In this section, the process of standard encoding color space and recently proposed encoding color space which is developed for reducing errors are introduced.

2.4.1 ITU-R Standard

2.4.1.1 Rec. ITU-R BT.709-6

The ITU-R BT.709 is the recommendation for HDTV image format parameters and values (ITU-R, 2015). In this standard, the YCbCr encoding color space was used for the color signal. The whole process of the signal is defined as EOTF (electro-optical transfer function), OETF (optical-electrical transfer function), etc.

For opto-electronic conversion, linear R, G, B optical signal converted to the non-linear R, G, B signal by using the opto-electronic transfer function as the following equations. The 0.45 power function is used in this equation.

$$\begin{cases} V = 1.099 \cdot L^{0.45} - 0.099 & for\ 1 \geq L \geq 0.018 \\ V = 4.500 \cdot L & for\ 0.018 > L \geq 0 \end{cases}$$

,where L is the luminance of the image [0,1]. V is the corresponding electrical signal. If the optical signal starts from X, Y, Z tristimulus value, the conversion matrix from X, Y, Z values to R, G, B values are used. By using the chromaticity coordinates of primary colors (Red, Green, Blue) and reference white, the 3x3 matrix can be induced. It means the color gamut of the display.

Table 3 The x, y of BT.709 primary colors

BT.709	x	y
Red	0.640	0.330
Green	0.300	0.600
Blue	0.150	0.060
White (D65)	0.3127	0.3290

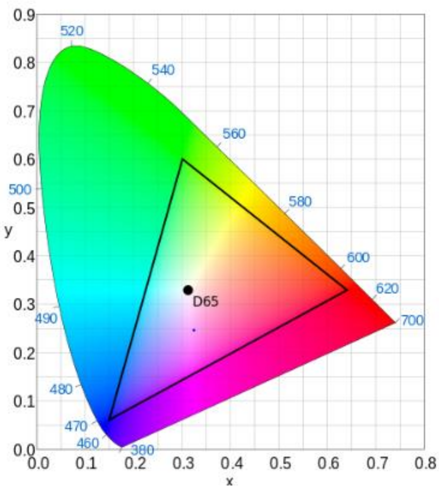

Figure 7 Color gamut of BT.709

The next step is to convert the non-linear R, G, B signals to the luminance signal and color-difference signal. The derivation of the luminance signal and the color difference signal is the following equations below.

$$E'_Y = 0.2126 \cdot E'_R + 0.7152 \cdot E'_G + 0.0722 \cdot E'_B$$

$$E'_{CB} = \frac{E'_B - E'_Y}{1.8556} = \frac{-0.2126 \cdot E'_R - 0.7152 \cdot E'_G + 0.9278 \cdot E'_B}{1.8556}$$

$$E'_{CR} = \frac{E'_R - E'_Y}{1.5748} = \frac{0.7874 \cdot E'_R - 0.7152 \cdot E'_G - 0.0722 \cdot E'_B}{1.5748}$$

, where E’ is the non-linear electrical signal corresponding for each. The signal is YCbCr encoding color space. Y is the luma signal and Cb and Cr are the chrominance signals. Cb and Cr represent the blueness-yellowness signal and redness-greenness signal respectively.

2.4.1.2 Rec. ITU-R BT.2020-2

The ITU-R BT.2020 is the recommendation for UHDTV image format parameters and values (ITU-R, 2015). In this standard, the YCbCr encoding color space is used for the color signals. BT.2020 is divided into two different signal formats: constant luminance and non-constant luminance. In the constant luminance, the final signal format is Y’CC’BCC’RC and in the non-constant luminance, the final signal format is Y’C’BC’R. For opto-electronic conversion, assumed linear R, G, B optical signal is converted to the non-linear R, G, B signal by using the opto-electronic transfer characteristics as in the following equations. The 0.45 power function is used in this equation. This step is identical for both the constant luminance and non-constant luminance as the following equation.

$$\begin{cases} E' = 1.099 \cdot E^{0.45} - 0.099 & for\ 1 \geq L \geq 0.018 \\ E' = 4.500 \cdot E & for\ 0.018 > L \geq 0 \end{cases},$$

,where E is luminance of the image [0,1]. E’ is the corresponding electrical signal. If the optical signal starts from X, Y, Z tristimulus value, the conversion matrix from X, Y, Z values to R, G, B values are used. By using the chromaticity coordinates of primary colors (Red, Green, Blue) and reference white, the 3x3 matrix can be induced. It means the color gamut of the display.

Table 4 The x, y of BT.2020 primary colors

BT.2020	x	y
Red	0.708	0.292
Green	0.170	0.797
Blue	0.131	0.046
White (D65)	0.3127	0.3290

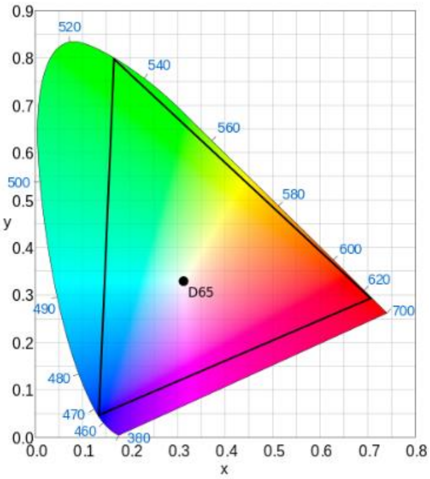

Figure 8 Color gamut of BT.2020

The next step is to convert the non-linear R, G, B signals to the luminance signal and color-difference signal. First, the constant luminance equations are following below.

$$Y'_C = (0.2126 \cdot E_R + 0.7152 \cdot E_G + 0.0722 \cdot E_B)'$$

$$\begin{cases} C'_{BC} = \dfrac{E'_B - Y'_C}{-2N_B} & for\ 0 \geq E'_B - Y'_C \geq N_B \\ C'_{BC} = \dfrac{E'_B - Y'_C}{2P_B} & for\ P_B \geq E'_B - Y'_C > 0 \end{cases}$$

$$\begin{cases} C'_{RC} = \dfrac{E'_R - Y'_C}{-2N_B} & for\ 0 \geq E'_R - Y'_C \geq N_B \\ C'_{RC} = \dfrac{E'_R - Y'_C}{2P_B} & for\ P_B \geq E'_R - Y'_C > 0 \end{cases}$$

,where P_B = 0.7910, N_B = -0.9702, P_R = 0.4969 and N_R = -0.8591.

The derivation of non-constant luminance is following:

$$Y'_C = 0.2126 \cdot E'_R + 0.7152 \cdot E'_G + 0.0722 \cdot E'_B$$

$$C'_B = \frac{E'_B - Y'}{1.8814}$$

$$C'_R = \frac{E'_B - Y'}{1.4746}$$

Non-constant luminance equations is the non-linear electrical signal for each corresponding. Y'_C and Y' are the luma signal and C_{BC}, C_{RC}, C_B, and C_R are the chrominance signals.

2.4.1.3 Rec. ITU-R BT.2100-2

The ITU-R BT.2100 is the recommendation about image parameter values for high dynamic range television for the use in producing an international program exchange using the Perceptual Quantization (PQ) and Hybrid Log-Gamma (HLG) methods (ITU-R, 2016). High Dynamic Range Television (HDR-TV) provides enhanced visual experience to viewers by providing images that have been produced to look correct on brighter displays. High dynamic range television production and display should make consistent use of the transfer function of one system.

The input signal, which is scene linear light, is converted into the electronic signal by using PQ OETF and HLG OETF function. The output signal of those OETF function is non-linear signal value. The PQ OETF(opto-electronic transfer function) is shown in the equation below:

$$E' = OETF[E] = EOTF^{-1}[F_D]$$

$$EOTF^{-1}[F_D] = \left(\frac{c_1 + c_2 Y^{m_1}}{1 + c_3 Y^{m_1}}\right)^{m_2}$$

$$Y = F_D/10000$$

$$m_1 = 2610/16384 = 0.1593017578125,\ m_2 = 2523/4096 \times 128 = 78.84375,$$

$$c_1 = 3424/4096 = 0.8359375 = c3-c2+1,\ c_2 = 2413/4096 \times 32 = 18.8515625,\ c_3 = 2392/4096 \times 32 = 18.6875$$

where E' is the resulting non-linear signal (R', G', B') in the range [0:1]. F_D, E, are as specified in the opto-optical transfer function.

The HLG OETF equation is expressed by

$$E' = OETF[E] = \begin{cases} \sqrt{3E} & 0 \le E \le 1/12 \\ a \cdot \ln(12E - b) + c & 1/12 < E \le 1 \end{cases}$$

$$a = 0.17883277,\ b = 1\text{-}4a,\ c = 0.5\text{-}a \bullet \ln(4a),$$

where E is a signal for each color component {RS, GS, BS} proportional to scene linear light normalized to the range [0:1]. E' is the resulting non-linear signal {R', G', B'} in the range [0:1].

The PQ EOTF (Electro-Optical Transfer Function) can be expressed as the reverse equation of OETF function. Unlike PQ function, the HLG EOTF function is the difference with its reverse of OETF function. It can be expressed with OOTF (Opto-Optical Transfer Function).

$$F_D = EOTF[\max(0,(1-\beta)E' + \beta)]$$

$$= OOTF[OETF^{-1}[\max(0,(1-\beta)E' + \beta)]]\ ,$$

where F_D is the luminance of a displayed linear component $\{R_D, G_D, \text{or } B_D\}$, in cd/m^2. E' is the non-linear signal {R', G', B'} as defined for the HLG Reference OETF. β is the variable for user black level lift.

OOTF function is following below equations.

$$F_D = OOTF[E] = \alpha {Y_S}^{\gamma-1} E$$

$$Y_S = 0.2627R_S + 0.6780G_S + 0.0593B_S\ ,$$

where $E = \{R_S, G_S, B_S\}$ is a signal for each color component proportional to scene linear light normalized to the range [0:1]. F_D is the luminance of a displayed linear component $\{R_D, G_D, B_D\}$. Y_S is the normalized linear scene luminance. α is the variable for user gain in cd/m^2. It represents L_W, the nominal peak luminance of a display for achromatic pixels. γ is the system gamma and the value $\gamma = 1.2$ at the nominal display peak luminance of 1,000 cd/m^2 is used.

$$OETF^{-1}[x] = \begin{cases} x^2/3 & 0 \le E \le 1/2 \\ \{\exp\left(\dfrac{x-c}{a}\right) + b\}/12 & 1/2 < E \le 1 \end{cases}$$

The values of parameters a, b, and c are as defined for the HLG Reference OETF. b and c are calculated as b = 0.28466892, c = 55991073 and $\beta = \sqrt{3(\frac{L_B}{L_W})^{1/\gamma}}$. L_W is nominal peak luminance of the display in cd/m^2 for achromatic pixels. L_B is the display luminance for black in cd/m^2.

2.4.2 ICtCp (Dolby)

ICtCp encoding color space is designed by Dolby for reproducing high dynamic range and wide color gamut images (Dolby, 2016). It is the orthogonal encoding color space, I is the luma signal and CtCp is the chrominance signal same with YCbCr. It mimics the human visual system, so the L, M, S cone signals are used for the optical signals. The L, M, S cone signal can be calculated from X, Y, Z tristimulus values with a 3x3 matrix.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.3592 & 0.6976 & -0.0358 \\ -0.1922 & 1.1004 & 0.0755 \\ 0.0070 & 0.0749 & 0.8434 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The linear L, M, S signals are converted to the non-linear electrical signal by using PQ (Perceptual Quantization) transfer function. PQ function was also suggested by Dolby for representing the HDR image which has the luminance level from 0 to 10,000 cm/m^2.

$$nonlinear\ LMS\ = \left(\frac{0.8359 + 18.8516 \cdot LMS^{0.1593}}{1 + 18.6875 \cdot LMS^{0.1593}}\right)^{78.8438}$$

After applying the PQ function, the ICtCp can be calculated from non-linear L, M, S values by using the 3x3 matrix as following:

$$\begin{bmatrix} I \\ Ct \\ Cp \end{bmatrix} = \begin{bmatrix} 0.5000 & 0.5000 & 0.0000 \\ 1.6137 & 3.3234 & 1.7097 \\ 4.3781 & -4.2455 & -0.1325 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}$$

2.4.3 Jzazbz

Jzazbz encoding color space was created by securing ICtCp encoding color space in the aspect of perceptual uniformity. The inputs are the XYZ tristimulus value, and the first step is converting the X, Y values to the X', Y'. Z value remains. It was optimized to enhance the hue linearity performance

$$\begin{bmatrix} X'_{D65} \\ Y'_{D65} \end{bmatrix} = \begin{bmatrix} bX_{D65} \\ gY_{D65} \end{bmatrix} - \begin{bmatrix} (b-1)Z_{D65} \\ (g-1)X_{D65} \end{bmatrix}$$

where b = 1.15 and g = 0.66.

Converting X', Y', and Z are calculated to make L, M, S cone signals.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.4148 & 0.5800 & 0.0146 \\ -0.2015 & 1.1206 & 0.0531 \\ -0.0166 & 0.2648 & 0.6685 \end{bmatrix} \begin{bmatrix} X'_{D65} \\ Y'_{D65} \\ Z_{D65} \end{bmatrix}$$

The OETF function takes the PQ function same with ICtCp.

$$L'M'S'\ = \left(\frac{0.8359 + 18.8516 \cdot LMS^{0.1593}}{1 + 18.6875 \cdot LMS^{0.1593}}\right)^{134.03}$$

The conversion to a Jzazbz encoding color signal is linearized by multiplying the 3x3 matrix, and converts the luma signal, I to J by fitting. It is in the same form with CAM02-UCS lightness equation.

$$\begin{bmatrix} I_z \\ a_z \\ b_z \end{bmatrix} = \begin{bmatrix} 0.5000 & 0.5000 & 0.0000 \\ 0.3650 & 0.6805 & 0.5427 \\ -0.0496 & -0.0494 & -1.2959 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}$$

$$J_z = \left(\frac{(1+d) \cdot I_z}{1 + d \cdot I_z}\right) - d_0, \qquad d = -0.56, \qquad d_0, = 1.62950499 \cdot 10^{-11}$$

where d = -0.56 and d_0 = $1.62950499 \cdot 10^{-11}$.

2.5 Summary

In this chapter, the literatures which are related to this research are reviewed in terms of color appearance terminology, color appearance model, color difference equations, CIE colorimetry, encoding color space, and chroma subsampling. In the psychophysical experiment, the test stimuli were made by using the different 3 encoding color spaces such as BT.709, ICtCp, Jzazbz, and chroma subsampling. The results were analyzed with color difference CIEDE2000 and color appearance in hue, chroma, lightness, compared to perception data.

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3. Experimental Design

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3.1 Introduction

In this research, the psychophysics experiment was conducted to investigate artifact estimation. The magnitude estimation method was used for the experiment and 10 participants estimated the magnitude of chroma subsampling artifact. Total of 150 test stimuli was evaluated in one session.

3.2 Experimental Setting

The experiment was conducted in a dark room by using an LCD monitor. The test stimuli were shown on the monitor. The LCD monitor was the 24-inch ColorEdge CG242W monitor as in Figure 9. The resolution of the monitor was 1920 x 1200 pixels. The maximum luminance of the monitor was 280cd/m^2. The monitor was calibrated to the sRGB color gamut.

Figure 9 Color Edge CG242W LCD monitor

For the psychophysical experiment, participants were seated in front of the monitor like Figure 10. The viewing distance from the monitor to participants was adjusted by each participant to minimize the effect of visual acuity. So, when participants evaluated the stimuli, they change the position of chair which can perceive the chroma subsampling artifact error well. Also, they can change their posture and distance from the monitor during the experiment, according to each stimulus.

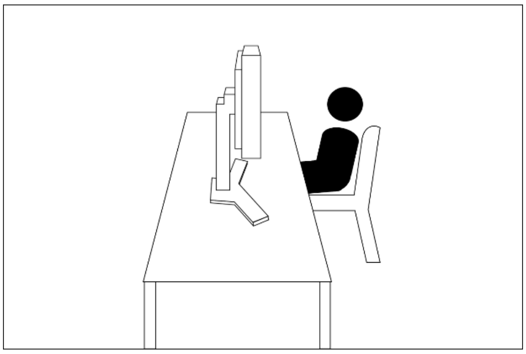


Figure 10 Experimental setting

For the psychophysics experiment, the psychophysics toolbox in MATLAB program was used. The Figure 11 shows the stimuli with the MATLAB program which was displayed on the monitor. After participants evaluated the test stimuli, they typed the evaluated value into the answer blank by using the keyboard.

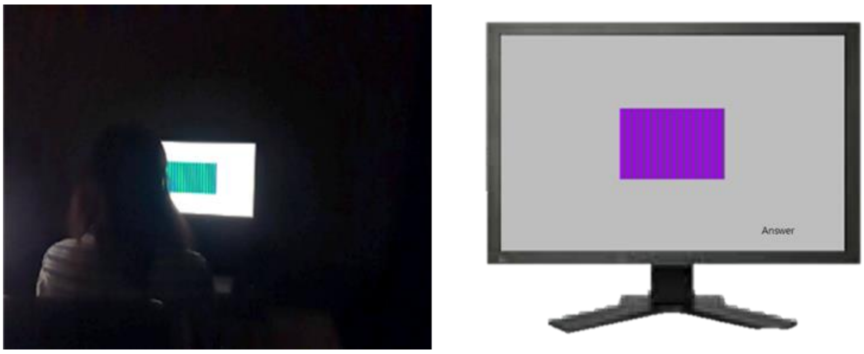


Figure 11 Experimental condition and scene

3.3 Monitor characterization

3.3.1 Color Measurement Instrument

In this research, the tele-spectroradiometer Konica Minolta CS-2000 was used for monitor measurement, as shown in Figure 12. The tele-spectroradiometer is used to measure the luminance and chromaticity accurately. The instrument can measure the spectral data from 380nm to 780nm with 1nm interval. The specification of CS-2000 is shown in table 5.

Figure 12 Konica Minolta CS-2000

Table 5 Konica Minolta CS-2000 specification

Wavelength range		**380 to 780nm**	
Wavelength resolution		0.9 nm / pixel	
Measuring angle	1	0.2	0.1
Measurement luminance range	0.003 ~ 5000 cd/m^2	0.075 ~ 125,000 cd/m^2	0.3 ~ 500,000 cd/m^2

3.3.2 Monitor Characteristics

Three primary colors of the monitor were measured with uniform steps of digital RGB values for finding the monitor's tone curve by using tele-spectroradiometer, Konica Minolta CS-2000, as in Figure 13. The measurement was conducted in a dark room condition. The color patch was shown in the EIZO monitor and measured.

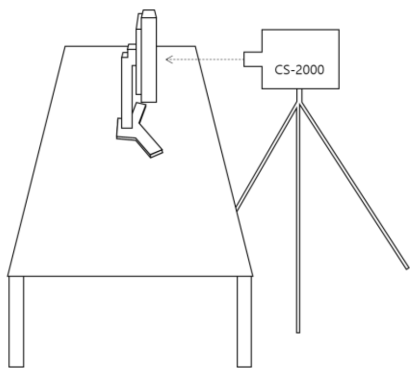
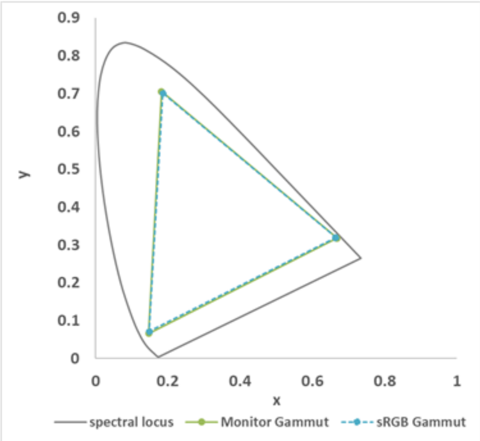
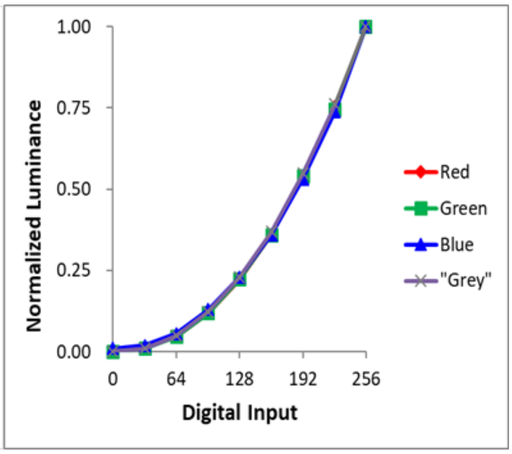


Figure 13 Measurment setting

Each digital RGB channel was divided into 9 steps from 0 to 255. Figure 14 (a) is color gamut (sRGB and monitor) on CIE x, y diagram. The sRGB and monitor gamut is similar to each other.

Figure 14 (b) shows the tone curve of each channel (Red, Green, Blue, White). In this figure, the x-axis is the value of an 8-bit digital input value, and the y-axis is normalized luminance value. Table 6 shows the X, Y, and Z tristimulus values and chromaticity values of measurement R, G, B.





(a) **(b)**

Figure 14 (a) Color gamut and (b) Tone curve of monitor

Table 6 Measured monitor color gamut

	X	Y(cd/m^2)	Z	x	y
Red	155.82	74.12	3.04	0.669	0.318
Green	49.75	192.74	30.82	0.182	0.705
Blue	51.80	23.36	277.95	0.147	0.066
White	244.93	277.83	302.34	0.297	0.337

3.3.3 Characterization Modelling

For characterization modelling, the GOG (Gain-Offset-Gamma) model (Berns, 1996) was used. The GOG model following below equations:

$$\text{RGB} = \begin{cases} 0 \quad , & \left(k_{g,rgb}\left[\frac{d_{rgb}}{2^N - 1}\right] + k_{o,rgb}\right)^{\gamma} < 0 \\ \left(k_{g,rgb}\left[\frac{d_{rgb}}{2^N - 1}\right] + k_{o,rgb}\right)^{\gamma} \quad , & \left(k_{g,rgb}\left[\frac{d_{rgb}}{2^N - 1}\right] + k_{o,rgb}\right)^{\gamma} \geq 0 \end{cases}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{R,max} & X_{G,max} & X_{B,max} \\ Y_{R,max} & Y_{G,max} & Y_{B,max} \\ Z_{R,max} & Z_{G,max} & Z_{B,max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

where RGB means the radiometric scholar value of each RGB channel. $k_{g,rgb}$ and $k_{o,rgb}$ are referred to as the gain and offset of each RGB channel. The d_{rgb} is the digital value. N is the number of bits. Gamma value is an exponential value for the non-linearity. For the characterization modeling, gain and offset is 1 and 0. Gamma value can be derived from Figure 14(b) tone curve and N is 8 for 8bits. Each column of the 3x3 matrix means the X, Y, Z value of max RGB. The final characterization model is following the below equations:

$$\text{RGB} = \begin{cases} 0 \quad , & \left(\left[\frac{d_{rgb}}{2^8 - 1}\right]\right)^{2.15} < 0 \\ \left(\left[\frac{d_{rgb}}{2^8 - 1}\right]\right)^{2.15} \quad , & \left(\left[\frac{d_{rgb}}{2^8 - 1}\right]\right)^{2.15} \geq 0 \end{cases}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 155.82 & 49.75 & 43.38 \\ 74.12 & 192.74 & 19.39 \\ 3.01 & 30.82 & 232.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

3.4 Experimental stimulus

3.4.1 Test pattern

The stripe pattern was used in this experiment. In the test pattern, two test color was used for making stripe pattern because the chroma subsampling artifact has occurred between neighboring pixels, especially on the edge of the color boundary. Thus, the stripe pattern was used to maximize the chroma subsampling artifact error. Each stripe has 25 pixels, the artifact error from chroma subsampling has 1 pixel. The total size of a test pattern is 832 x 500 pixels. Figure 15 shows an example of a test pattern. The luminance of the background was 120cd/m^2.

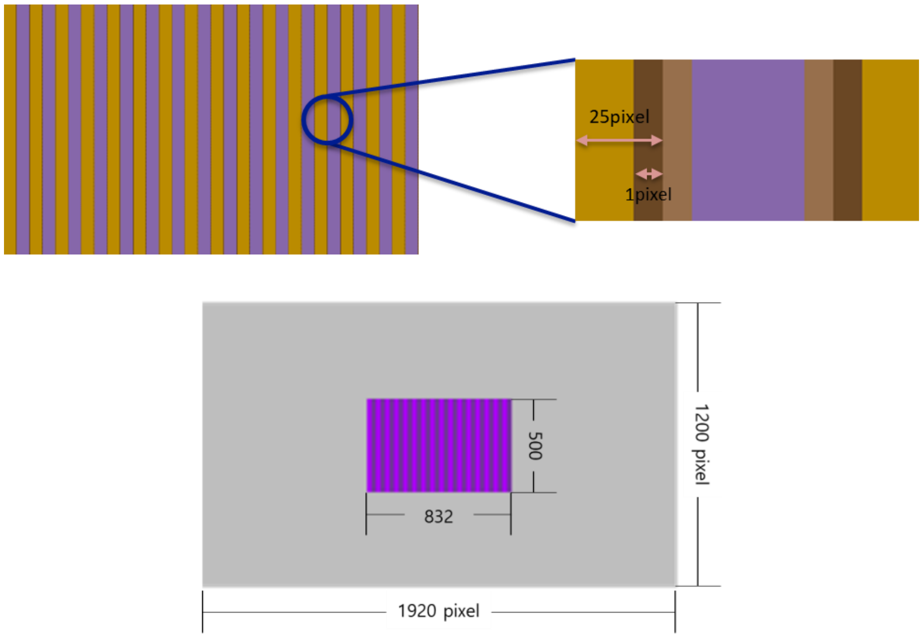


Figure 15 Example of the experiment test stimulus

3.4.2 Test stimulus

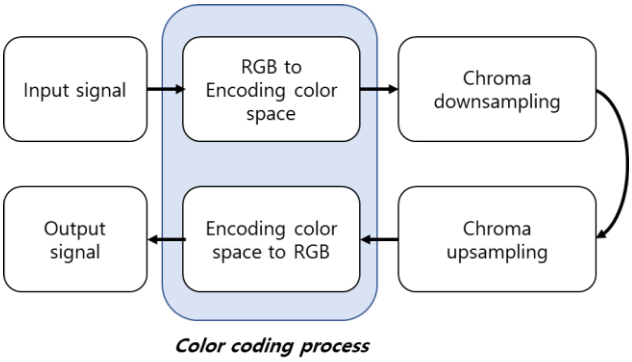


Figure 16 The image color coding process

The number of test pattern used in the experiment was 150. The test stimuli were produced as the process in Figure 16. The R, G, B input signals were converted into the X, Y, Z tristimulus values by using the BT.709 color gamut. Then the X, Y, Z tristimulus values were converted into encoding color space. In this process, three different encoding color space was used: YCbCr, ICtCp, and Jzazbz.

After converting the RGB color to encoding color space, the 4:2:0 chroma subsampling step was implemented right after. The average 4:2:0 method was used for chroma subsampling as Figure 17.

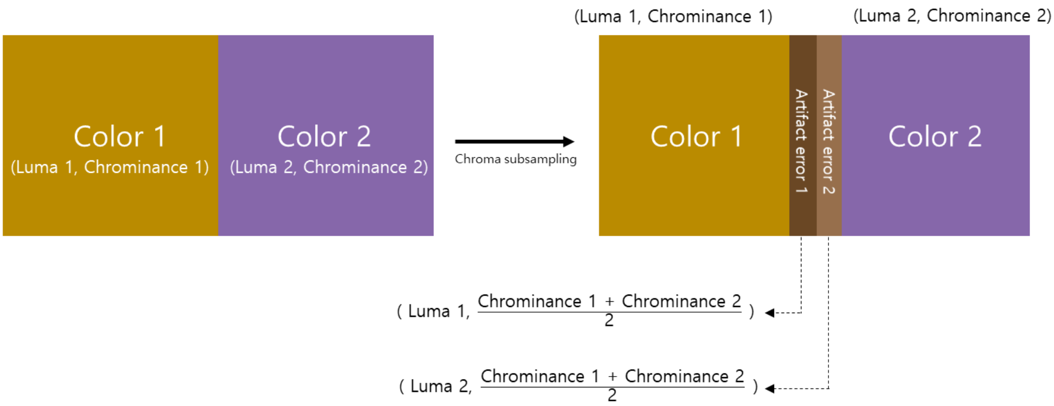


Figure 17 Average 4:2:0 chroma subsampling method

In this method, luma information maintains and chrominance information was averaged with neighboring color. Thus, there are two different artifact errors in one test stimulus.

A total of 150 test stimuli was randomly selected. The 120 test stimuli were selected from three encoding color spaces, each of 40. The other 30 test stimuli didn't have any artifact. Figure 18 shows the color distribution of test colors which is expressed on CIELAB color space.

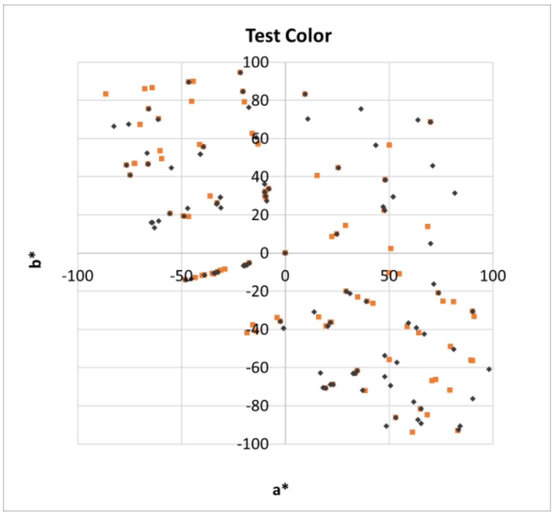


Figure 18 Color distribution of test colors on CIELAB color space

3.4.3 Reference color

In this experiment, the psychophysical experiment was conducted using the magnitude estimation method. When the magnitude estimation experiment is used, a reference is needed. The reference patch was selected from the various color combinations randomly. The Figure 19 shows the reference patch and L*a*b*, dL* and dE2000 of the reference patch are shown in below table 7. Table 8 shows the average lightness difference and color difference of test stimuli.

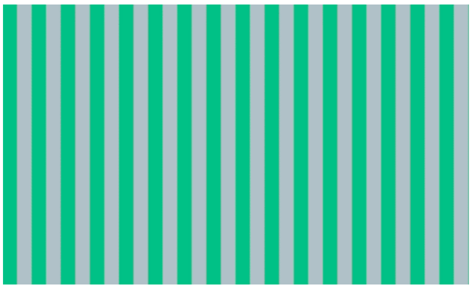


Figure 19 Reference patch

Table 7 Specification of reference patch

Reference patch	Color 1	Subsampled 1	Color 2	Subsampled 2
L*	69.07	68.45	77.81	78.50
a*	55.35	-26.10	0.44	-29.46
b*	20.74	10.57	-0.07	11.92
dL*	0.62		0.69	
dE2000	55.46		23.02	

Table 8 Average lightness difference and color difference of test stimuli

Test stimuli	| Color 1-Subsampled 1|	| Color 2 – Subsampled 2|
dL*	2.79	3.50
dE2000	18.35	19.39

3.5 Experiment procedure

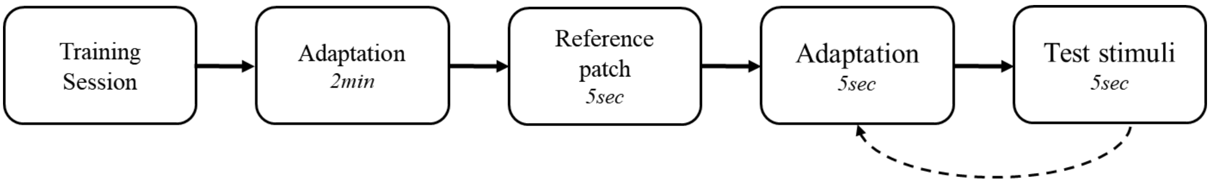


Figure 20 The workflow of psychophysical experiment

Before starting the main experiment, the training session was needed to make participants familiar with the magnitude estimation method. In the training session, the 4 test stimuli which have different chroma subsampling error, were used. The result of the training session was not recorded.

In the main experiment, first, the adaptation was conducted for 2 minutes. The adaptation scene has the same luminance value as the neutral gray background of test stimuli. Background gray luminance was 120cd/m^2.

Second, the reference stimulus was shown in the monitor for 5 seconds for the magnitude estimation. Assuming that the participants can evaluate the test stimuli well with their own criteria, participants could see the reference stimulus only at the first scene in a session.

Third, Participants evaluated the test stimuli. A total of 150 test stimuli was used in the main experiment. The participant evaluated the test stimuli by comparing the reference stimulus which has value of 5. It was the same task with the training session. If participants perceived the 1-pixel artifact error more than reference, they answered over 5 and if not, they evaluated the test stimulus under 5 or zero. There was no limitation to the maximum answer.

The whole process was repeated 2 times by 2 sessions per participant. The stimuli were shown on the monitor randomly, and the order of stimuli was changed each session.

3.6 Participants

In this experiment, a total of 10 participants evaluated the artifact error. Before starting the experiment, participants did the Ishihara test to check whether he or she has a normal color vision. Ishihara test is a color perception test for finding color deficiencies. Most test plate consists of number. Figure 21 is an example of the Ishihara test with the number. The participants answer the number they can see in the test.

All the participants have a normal color vision. They were all university students who were aged between 22-25. Among them, two were males and eight were females.

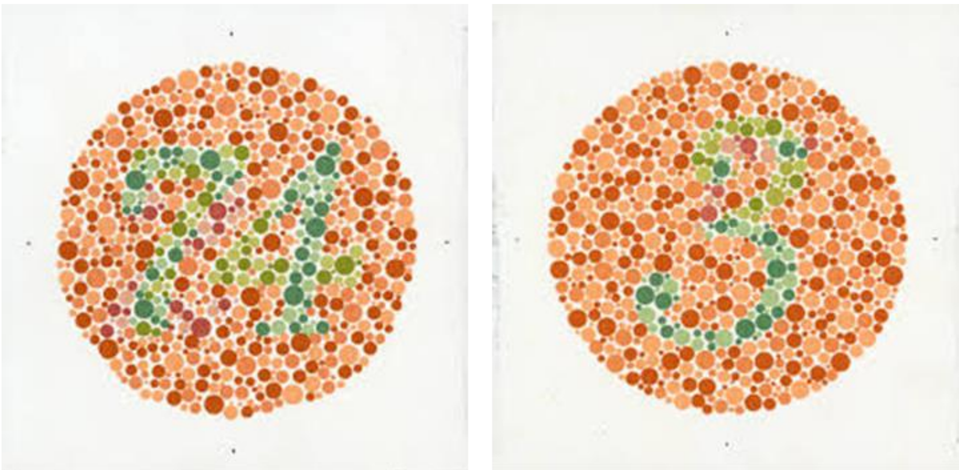


Figure 21 Example of Ishihara test image

3.7 Data analysis method

3.7.1 Pearson correlation coefficient

Pearson correlation coefficient has a meaning of linear correlation between two variables according to the Cauchy-Schwarz inequality. The value is decided only between +1 and -1, where +1 means a perfect positive linear correlation, r_{xy} means no linear correlation, and -1 is a perfect negative linear correlation. Pearson's correlation coefficient, especially for a sample, is commonly denoted as a r_{xy}. The sample Pearson correlation coefficient can be calculated by using estimates of the covariances and variances which is based on a given paired data {(x1,y1),(x2,y2),….,(xn,yn)} consisting of n pairs:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})\,(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\,\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}}$$

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

where n is the number of data, $\overline{y}$ have the same equation with $\overline{x}$. It is the average value of each data such as observer data. x_i, y_i are the individual data points. In this research, it is used for deciding baseline data, where factors such as a difference of luminance, hue, chroma, and color difference have a high correlation against perception data. It is used for finding surround color effect of human perception in experimental stimuli.

3.7.2 Coefficient of variation (CV)

The coefficient of variation is defined as a degree of scattering by using standard deviation and mean value. Especially, if the average of data has a large difference in scale, it is useful to evaluate the distribution. The correlation between CV can be expressed as a percentage or ratio of the standard deviation to the mean:

$$\mathrm{CV} = \frac{\sigma}{\mu} = \frac{100\sqrt{\sum(X_i - \overline{X})^2/N}}{\overline{X}}$$

where σ is the standard deviation and μ is the mean value of the data set and N is the number of data.

In this research, the CV value was used for evaluating the repeatability. If participants did the experiment very well with perfect performance, the CV value should be zero. In the repeatability test, calculating CV value needs two sets of data:

$$\mathrm{CV} = \frac{100\sqrt{\sum(X_i - Y_i)^2/N}}{\overline{Y}}$$

where N is the number of data in X and Y sets and $\overline{Y}$ is the mean of the Y set.

3.8 Summary

In this chapter, the experimental design was shown. The test patch has a stripe pattern to simplify and maximize the chroma subsampling artifact error. The color combination was needed for making a test patch, and it was selected randomly. A total of 150 test stimuli was used for the experiment. Among the 150 colors, 30 test stimuli didn't have any artifact. The main experiment was conducted by using the magnitude estimation which is one of the psychophysical methods. For data analysis, the Pearson correlation coefficient and CV value were used. The collected perception data was used to make an assessment artifact metric that is based on human perception.

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4. Effect Factors of Artifact Estimation

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4.1 Introduction

When participants estimate the artifact error, various factors affect perception. In this chapter, the effect factors of artifact estimation are determined by analyzing the experimental results. There are 3 criteria for finding out factors from the experimental stimuli. 1) CIEDE00 between original color and chroma subsampled artifact, 2) surrounding colors, 3) neighboring colors. Moreover, there is another effect factor related to pixel structure. Figure 22 shows the effect factors in experimental stimuli. C1 and C2 mean original colors, A1 and A2 mean the color of chroma subsampling artifact. A1 is the artifact from color 1 and A2 is the artifact from color 2.

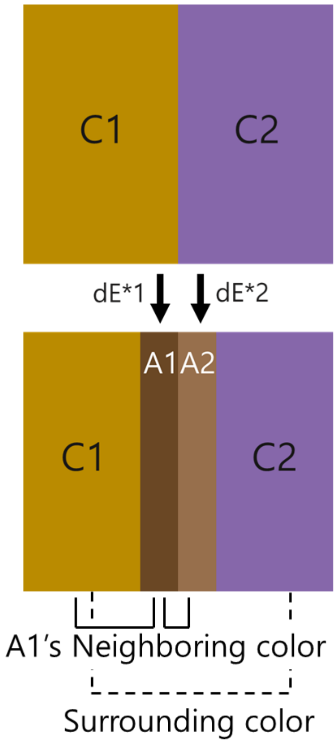


Figure 22 Example of the effect factors in test stimuli

4.2 Observer Performance

4.2.1 Reproducibility

To check the outliers, the reproducibility of each observer was tested. Table 9 represents the correlation coefficient of each participant. The correlation between participants' response and average responses are calculated. Most of the participants have an acceptable correlation. P9 has the lowest correlation with average responses than the others. As a result, all the data from 10 participants were used for result analysis.

Table 9 Reproducibility of each participants

	Participants									
Correlation	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
R	0.860	0.802	0.833	0.827	0.862	0.884	0.824	0.781	0.763	0.831

4.2.2 Repeatability

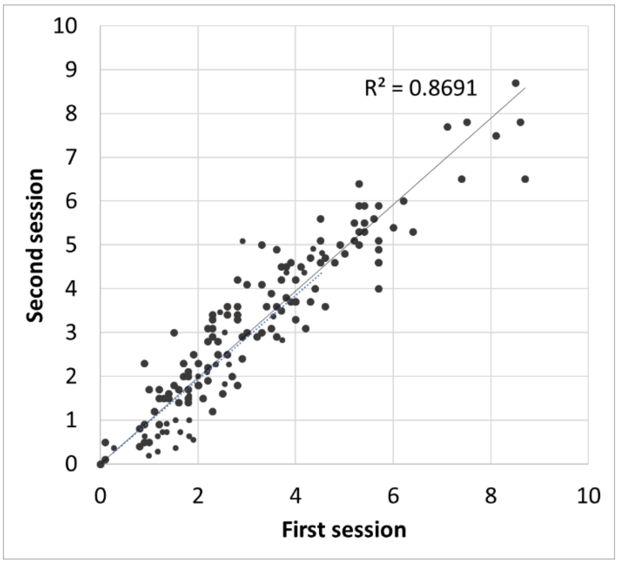


Figure 23 Repeatability

The repeatability can measure whether the experiment can be reproduced in its entirety. In this experiment, observers repeat the experiment which has the same stimuli set with a different order of test stimuli. Figure 23 represents the repeatability between two sessions. The r^2 value was high enough. So, the whole experiment data can be acceptable.

4.3 Effect of color difference between original color and subsampled color

The first effect factor is the color difference between original color and chroma subsampled color. The difference between original color and chroma subsampled color can be calculated like Figure 22.

There are various color appearance components that can affect the artifact estimation: lightness, hue, chroma, etc. Thus, to investigate which color component affects artifact estimation most, the four different color components, lightness, chroma, hue and color difference, are tested. These factors are analyzed with artifact estimation. Artifact estimation data is the average response of all the participants.

Furthermore, there are two differences in one test stimuli because there are two original colors and two subsampled artifact colors which are occurred on the edge of original color changing (i.e. set 1(C1-A1), set2 (C2-A2)). However, which difference set is used for estimating the magnitude of artifact error is not clear. Thus, two cases of the result are analyzed. Case 1 is comparing the maximum of the two difference sets with artifact estimation data. Case 2 is comparing the average difference between two of the difference sets with artifact estimation data. Figure 22 shows the case 1 result and Figure 23 shows the case 2.

The artifact estimation data is expressed by perception data. It was used as a rescaling data to match the data scale with differences scale. The rescaling factor is 5.3052.

$$perception\ data = rescaling\ factor \times artifact\ estimation\ data$$

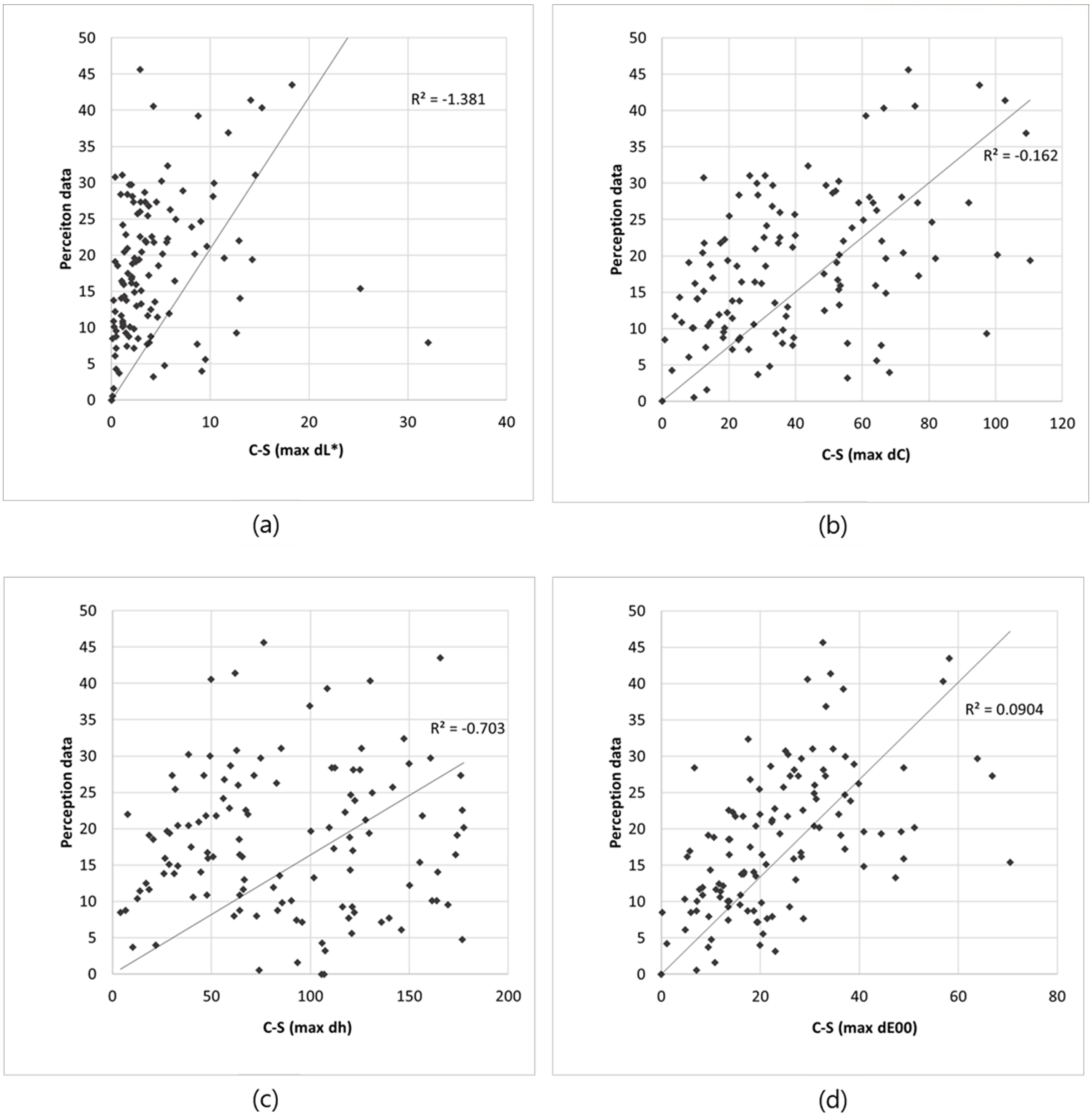
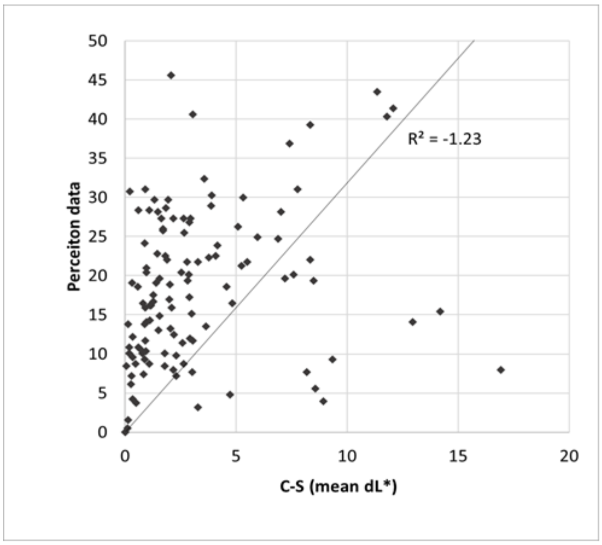


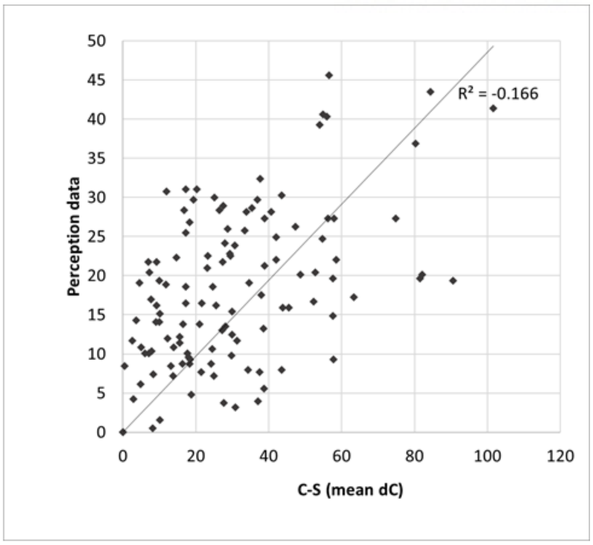
Figure 24 Max difference of color components (original – subsampled)

Table 10 Maximum data of color components' difference

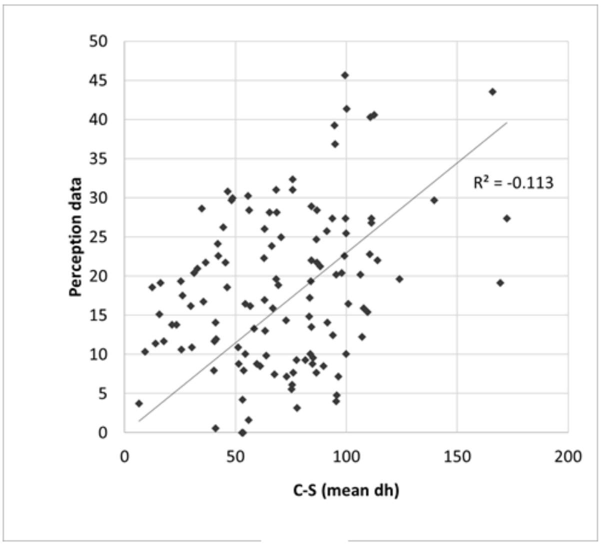
	Maximum data of color components' difference			
Color Component	ΔL*	ΔC*	Δh	CIEDE00
R value	0.285	0.479	0.067	0.559



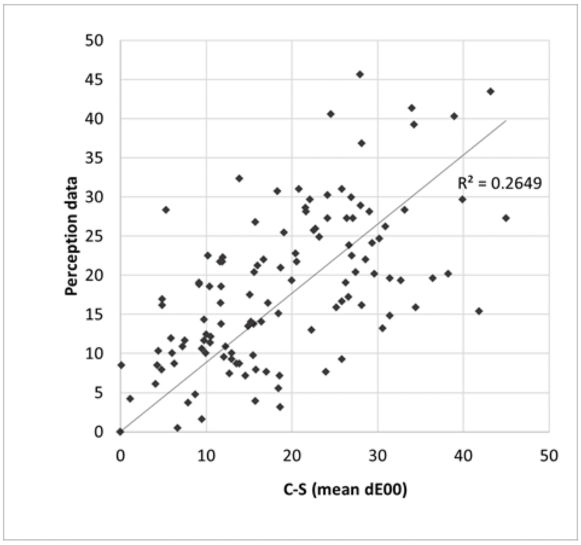
(a)



(b)



(c)



(d)

Figure 25 Mean difference of color components (original – subsampled)

Table 11 Mean data of color components' difference

	Mean data of color components' difference			
Color Component	ΔL*	ΔC*	Δh	CIEDE00
R value	0.295	0.512	0.330	0.611

In Figure 24 and Figure 25, the x-axis is the absolute value of difference error between original color and chroma subsampling artifact color, where (a) difference of luminance, (b) difference of chroma, (c) difference of hue and (d) color difference (CIEDE00). The y-axis is the perception data. Case 1 is the maximum value of two error sets in Figure 24 and case 2 is the mean value of two error sets in Figure 25. As shown in table 10 and 11, (d) color difference has the highest correlation compared with human perception data on both cases and case 2 has a better correlation than case 1.

As a result, the color difference between original stimuli and chroma subsampled stimuli can be determined as a chroma subsampling error in the artifact estimation. Furthermore, the result can be analyzed that people estimate the artifact with a more complicated perception because of the highest correlation of mean color difference.

4.4 Surrounding Colors Effect

The second effect factor is the surrounding colors. The surrounding colors represent a wider range of ambient colors. The C1 and C2 in Figure 26 are the surrounding colors of A1.

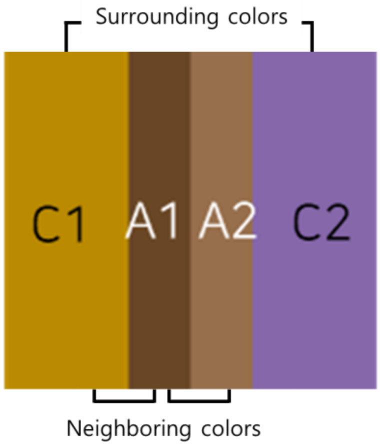


Figure 26 Surrounding and neighboring colors of A1

To investigate the effect of the surrounding colors, the qualitative analysis was used. The color difference between the surrounding colors is used for analysis. From the result of the color difference in chapter 4.3, the result can be divided into two parts: underestimation and overestimation, comparing with artifact estimation data.

In the underestimation part, there is a common characteristic of surrounding colors that have a large color difference. The effect in surrounding colors is when the color difference between surrounding colors become larger, the artifacts are underestimated. Figure 27 represents the example of the surrounding colors effect. Figure 27 (a) is the test stimulus that has a large color difference between surrounding colors and (b) shows the test stimulus which has a small color difference between surrounding colors. However, both test stimulus has a similar color difference between original color and subsampled color. (a) looks less artifact than (b), although both have a similar actual color difference between original color and subsampled color.

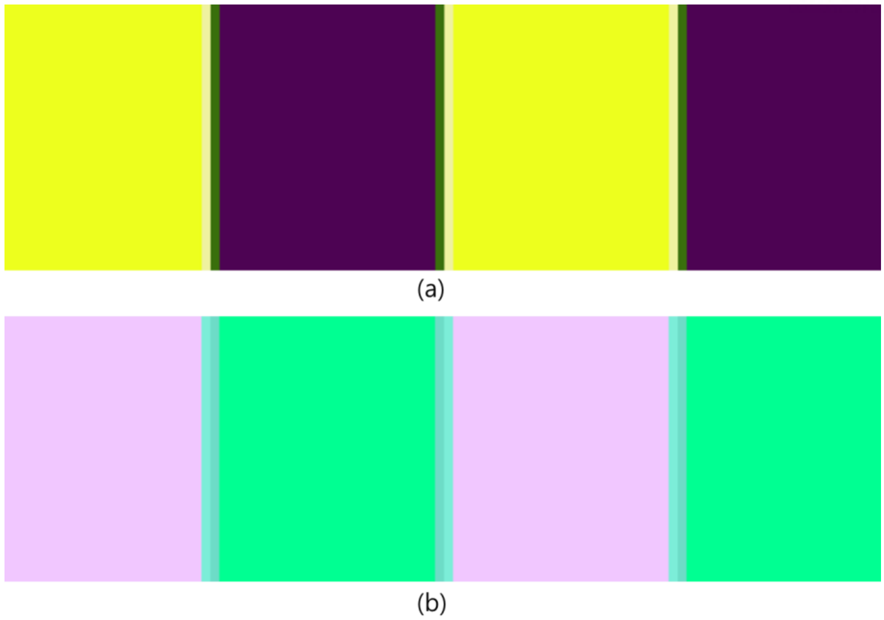


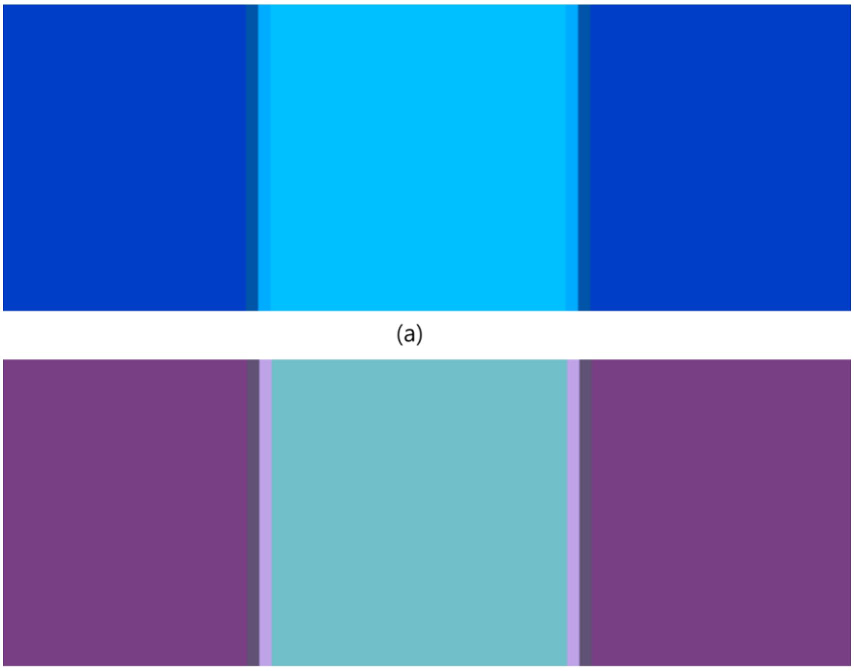
Figure 27 Example of surrounding colors effect (a) Large dE00 between surrounding colors (b) Small dE00 between surrounding colors, with similar mean dE00 (original – subsampled)

4.5 The Neighboring Colors Effect

The third effect factor is the neighboring colors. The neighboring color can be defined as the nearest colors from the center. The center color is a criterion for deciding the nearest color.

In this experiment, the neighboring colors are almost the same as the chroma subsampling error in test stimuli, because original colors locate nearby the subsampled artifact colors in test stimuli. It also has the same color difference value with the chroma subsampling error (mean dE00). So, the qualitative analysis was carried out about the neighboring colors effect.

A common characteristic appears at the stimuli which have a small color difference between neighboring colors and center color. The characteristic is that if the center color has a small color difference with one of the neighboring colors, people can't perceive the artifact well. Figure 28 represents the example of stimulus having the neighboring color effect of artifact estimation.



(a)

(b)

Figure 28 Stimulus having neighboring colors effect (a) Small dE00 between neighboring colors (b) larger dE00 between neighboring colors, with similar dE00 (surrounding colors)

4.6 Effect of Pixel Structure

The fourth effect factor is the pixel structure of the LCD monitor. The stimuli which have no errors were also included when participants evaluate the stimuli. However, the participants evaluated that stimuli have 4:2:0 chroma subsampling artifact. Figure 29 shows the perception data of no-artifact stimuli.

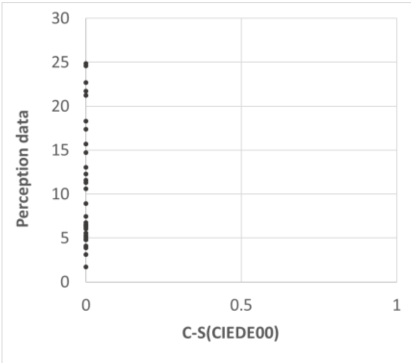


Figure 19 Perception data of no-artifact stimuli

To find the reason why participants perceived the artifact although there is no-artifact in stimuli, each stimulus was checked by using the Lupe, which is the magnifying glass. The perception error was occurred because of the pixel structure of an LCD monitor as a result of observation.

The LCD monitor has the RGB structure, one pixel consists of R, G, B sub-pixels. Figure 30 shows the R, G, B subpixel structure of LCD display.

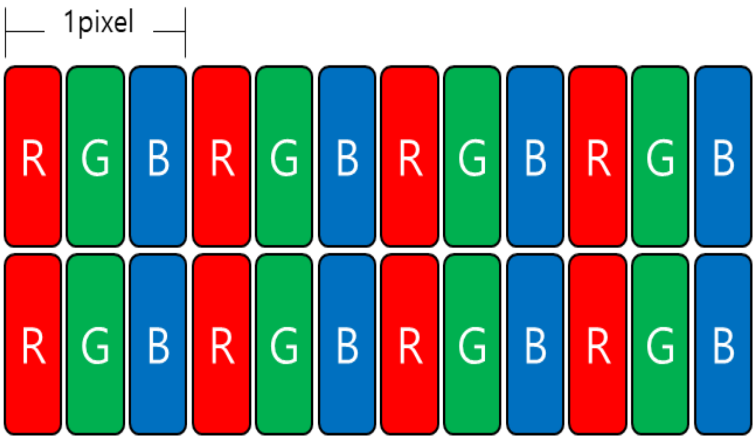


Figure 20 LCD pixel structure

Intentionally, the colors of a pixel should be produced by R, G, B. However, if color 1 and color 2 have large differences especially on red channel and green channel, G, B, R were perceived like one-pixel.

Figure 32 is the real pixel image of the stimulus. In Figure 31 and 32, the edge of the color-changing looks blue pixel line because the GBR value on the edge was just blue.

However, this factor is not considered for modeling because it will be changed by pixel structure.

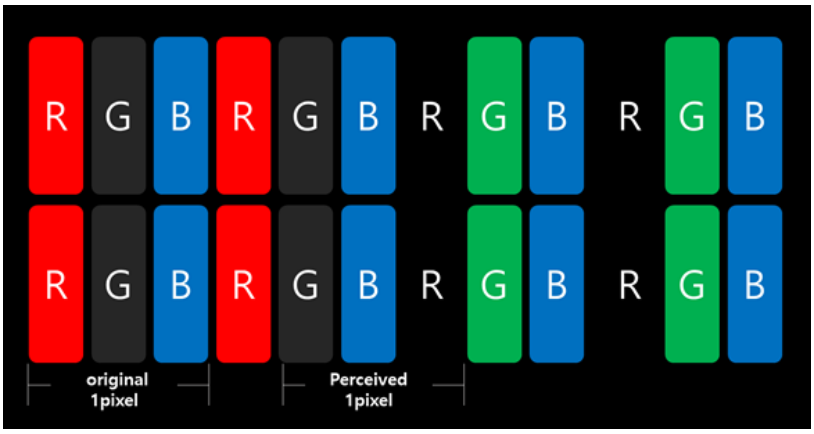


Figure 31 Example of the pixel structure effect

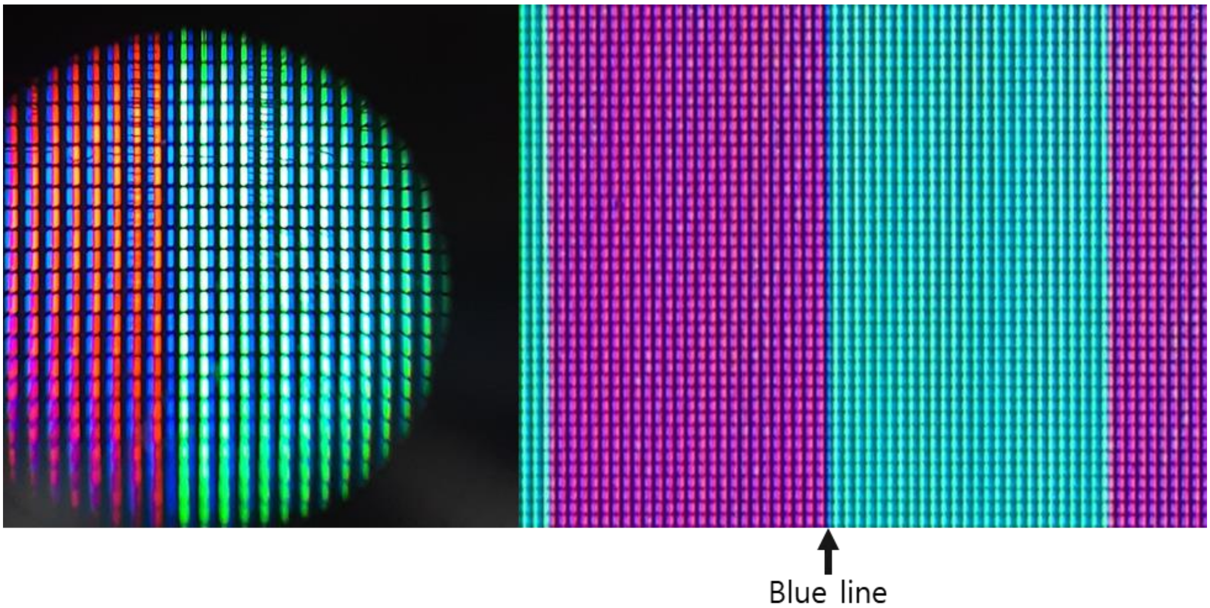


Figure 32 The actual pixel structure of Figure 30

4.7 Summary

In this chapter, the effect factors which affect the artifact perception are analyzed. There are four effect factors: the color difference between original color and subsampled color, surrounding colors, neighboring colors and monitor pixel structure.

In the color difference between original color and subsampled color, the difference of various color components (lightness, chroma, hue, and color difference) is analyzed by two cases, max and mean. According to results, the mean dE00 is the component having the highest correlation with artifact perception data among the color components.

The surrounding colors and neighboring colors are related to the colors which are located around the artifact colors. Thus, the color difference between the surrounding colors is the second effect factor and the color which is located at the nearest with the artifact is the third effect factor.

As a result, people can’t perceive the artifact well, when the surrounding colors have a large difference. Also, when the neighboring color has a similar color with the nearest color, people can’t perceive the artifact.

The pixel structure effect is the effect of LCD monitor sub-pixel. The LCD monitor used in the experiment has the R, G, B sub-pixel structure. The red sub-pixel is located next to the blue sub-pixel and it makes the perception error. People perceive the artifact although the stimuli have no artifact.

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5. Modeling the Chroma Subsampling Artifact Assessment Metric

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5.1 Introduction

The modeling process is described in this chapter. The chroma subsampling artifact assessment metric was modeled for applying to the image based on the psychophysical experiment. Thus, the metric was developed with a more complicated image than the test stimulus pixel by pixel. The effect factors found were used for metric modeling: 1) the color difference between the original image and subsampled image, 2) the surrounding colors effect, and 3) the neighboring colors effect.

In the metric, three images are needed. Each image is used to decide weighting function depending on the effect factor: the original image (O), blurring image (B) and subsampled image (S). The converted image which is done chroma-subsampling is named with the subsampled image (S) and the blurring image (B) has been blurred from the original image. Figure 33 shows the simple scheme of modeling by using the effect factors.

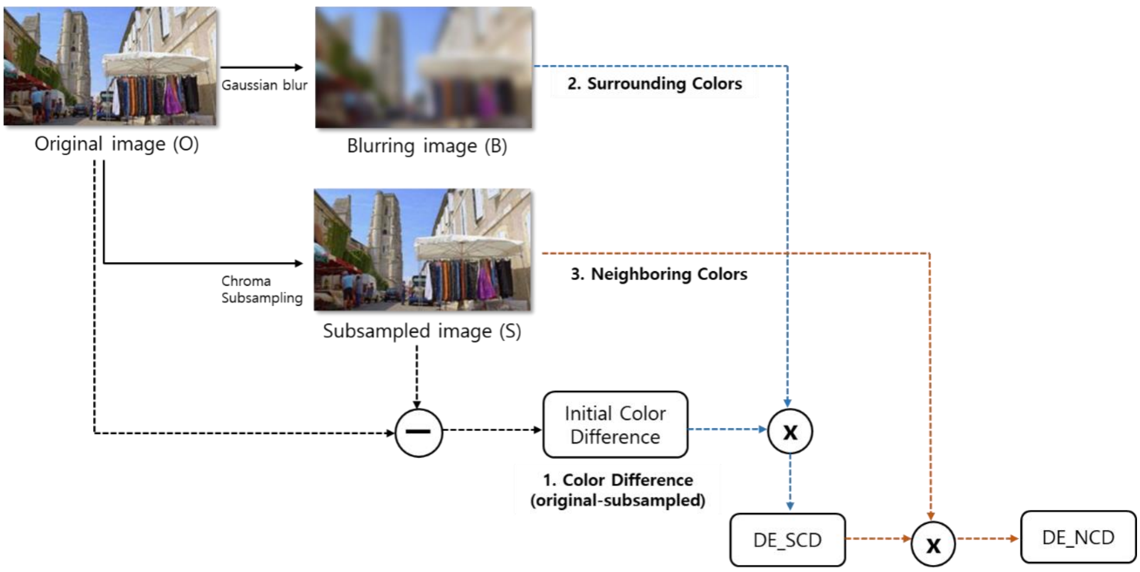


Figure 33 The simple process of metric

5.2 Modeling based on Color Difference

First of all, the metric was modeled based on the color difference between original color and subsampled color, because it has the highest correlation with estimation data. Thus, the CIEDE00 of the original image and the subsampled image was used for the first step of modeling the metric.

When calculating the CIEDE00 between the original image and subsampled image, the color values of the original pixels and subsampled pixel, which is located in the same position, were used like the following equation:

$$ICD = E_{00}[O(i,j),S(i,j)] ,$$

where ICD stands for the Initial Color Difference, O mean the CIELAB value of original pixel which positioned on (i,j) and S is the CIELAB value of subsampled image which positioned on (i,j).

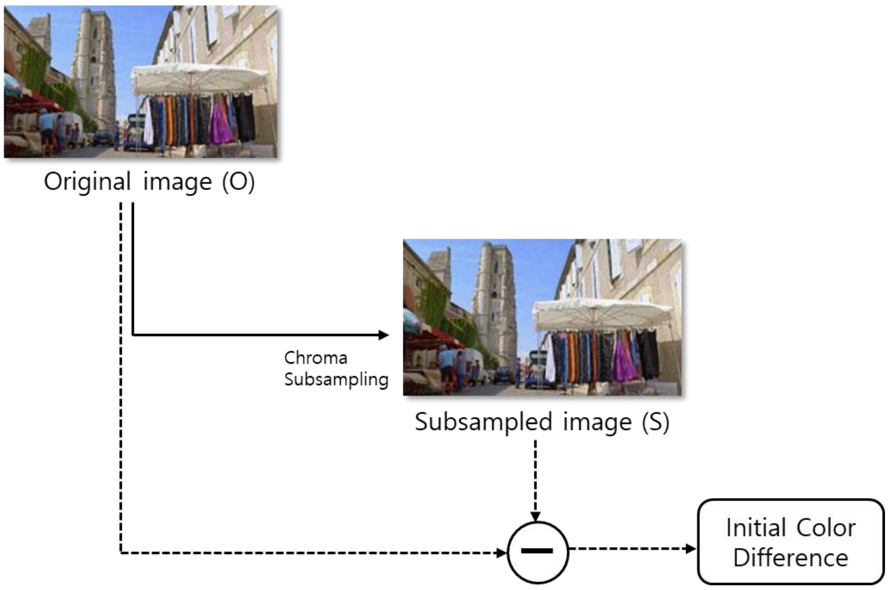


Figure 34 Structure of Initial Color Difference

5.3 Modeling based on Surrounding Colors Effect

Secondly, the surrounding color effect is applied for the ICD. The effect is that if the surrounding colors have a large color difference (CIEDE00) to each other, participants can't perceive the artifact well. For applying surrounding pixels, the blurred image from the original image is needed. Because most of the image has more complicated surrounding pixels than test stimuli in this experiment. The surrounding color means the wider range of pixels color. So, the blurring method was used to establish the area which affects artifact estimation. It means that the blurred image is used to surround pixels color information.

When blurring the original image, the Gaussian filter was used. Gaussian filter is one of the image filtering methods which have a mask of gaussian distribution with a standard deviation of 0.5. To optimizing the metric, the whole surround pixel condition was considered from a blurred image.

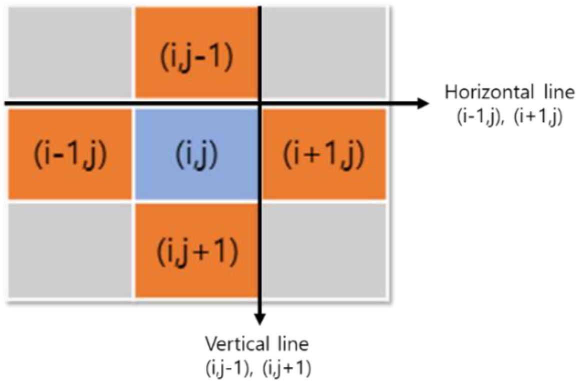


Figure 35 The pixel structure of image

Figure 35 shows the simple scheme of the surrounding pixel condition. The color difference between surround pixels is calculated for weighting function, horizontal and vertical. The horizontal surrounding condition is the color difference between (i,j-1) and (i,j+1) and the vertical surrounding condition is the color difference between (i-1,j) and (i+1,j).

The minimum color difference between the horizontal condition and the vertical condition is expressed by SCD (Surrounding Color Difference). Because, if the minimum color difference has a large color difference between surrounding colors, the other is always larger than the minimum. The SCD was used for the weighting function. The exponential function is used for the weighting function with SCD value. Figure 36 shows the weighting exponential function. The x-axis is the SCD, and the y-axis is the weighting function. It has a smaller weighting function when SCD is larger.

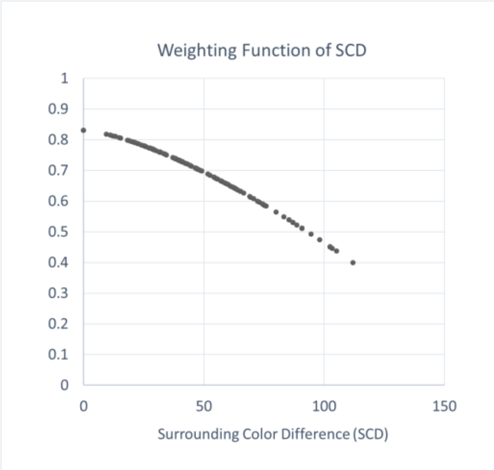


Figure 36 Weighting function of Surrounding Color Difference

The equation of weighting function can be expressed as followings:

$$SCD = \text{Min}\ (E_{00}[B(i\text{-}1,j),B(i+1,j)],\ E_{00}[B(i,j\text{-}1),B(i,j+1)])$$

$$DE_{SCD} = ICD * \left(\left(\frac{-0.5304 * SCD}{100}\right)^{1.3914} + 0.9294\right)$$

, where B means the blurred image which is represented in Figure 33, and DE_{SCD} means the result of the second step on the assessment metric. The weighting function is multiplied into the Initial Color Difference.

Figure 37 represents the simple scheme of metric algorithm including step 1 and step 2.

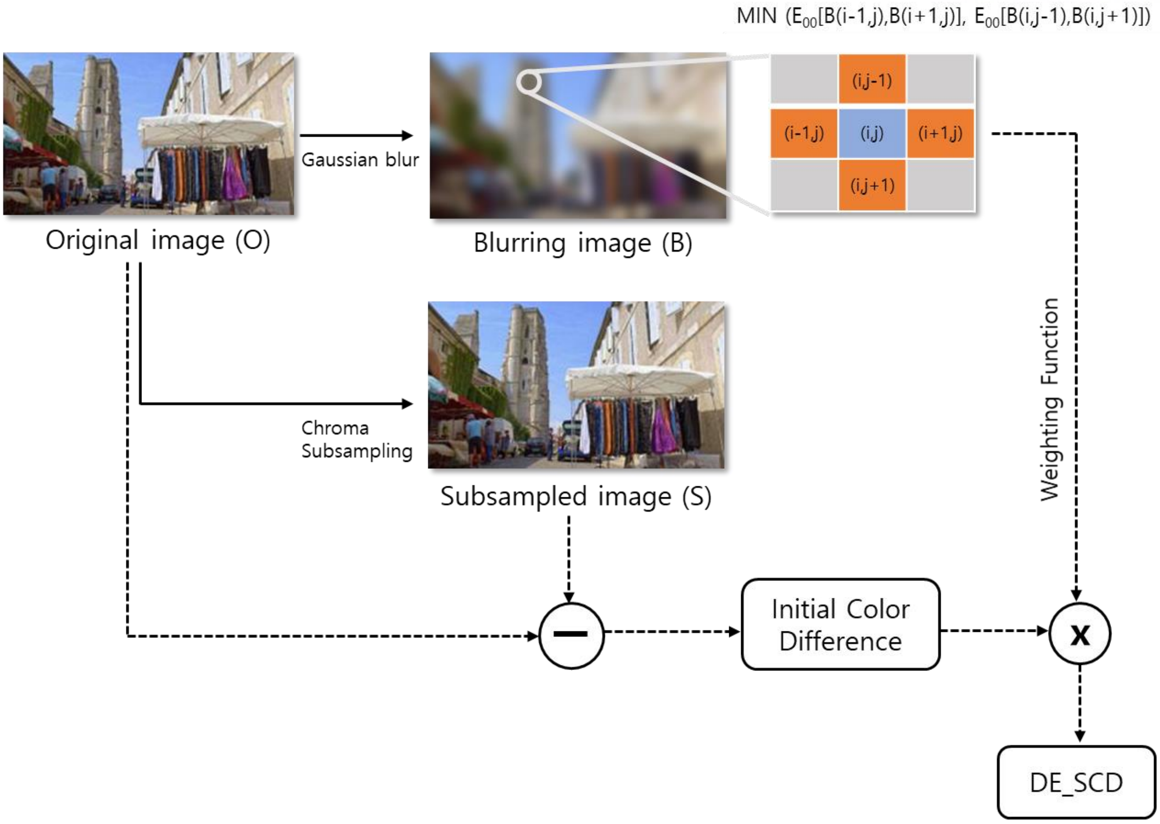


Figure 37 Structure of Surrounding Colors Difference based on ICD

5.4 Modeling based on Neighboring Colors Effect

Finally, the neighboring colors effect was used for modeling the metric. The finding of neighboring pixel colors is that people can perceive artifact well when the artifact has a similar color with the neighboring colors.

The neighboring colors effect is applied after calculating the DESCD. For applying neighboring colors effect on the image, the subsampled image is used. The color difference between the center pixel and neighboring pixels which are located the nearest of all directions (up, down, left, and right) is named Neighboring Color Difference (NCD). The center pixel represents (i,j) and neighboring pixels represents (i,j+1), (i,j-1), (i+1,j) and (i-1,j) in Figure 35.

The minimum value of NCD is used for the weighting function. If the minimum value of NCD is used for the parameter of the weighting function, Figure 38 shows the weighting function of NCD. When the minimum value of NCD is larger than 4, the weighting function is almost 1.

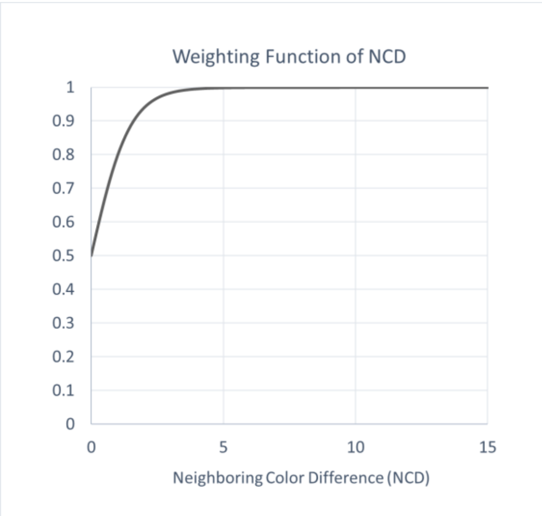


Figure 38 Weighting function of Neighboring Colors Difference

The equations of neighboring colors effect are as following:

$$NCD = MIN\,(E_{00}[S(i,j),S(i,j-1)],\ E_{00}[S(i,j),S(i,j+1)], E_{00}[S(i,j),S(i-1,j)],\ E_{00}[S(i,j),\ S(i+1,j)])$$

$$DE_{NCD} = DE_{SCD} * \frac{1}{1+e^{-(1.352345*NCD)}}$$

, where NCD is the Neighboring Color Difference and DE_{NCD} is the result of final metric.

Figure 39 shows the whole algorithm of 4:2:0 chroma subsampling error assessment metric. This artifact assessment metric will be shown with image form and can be calculated the error value of each pixel.

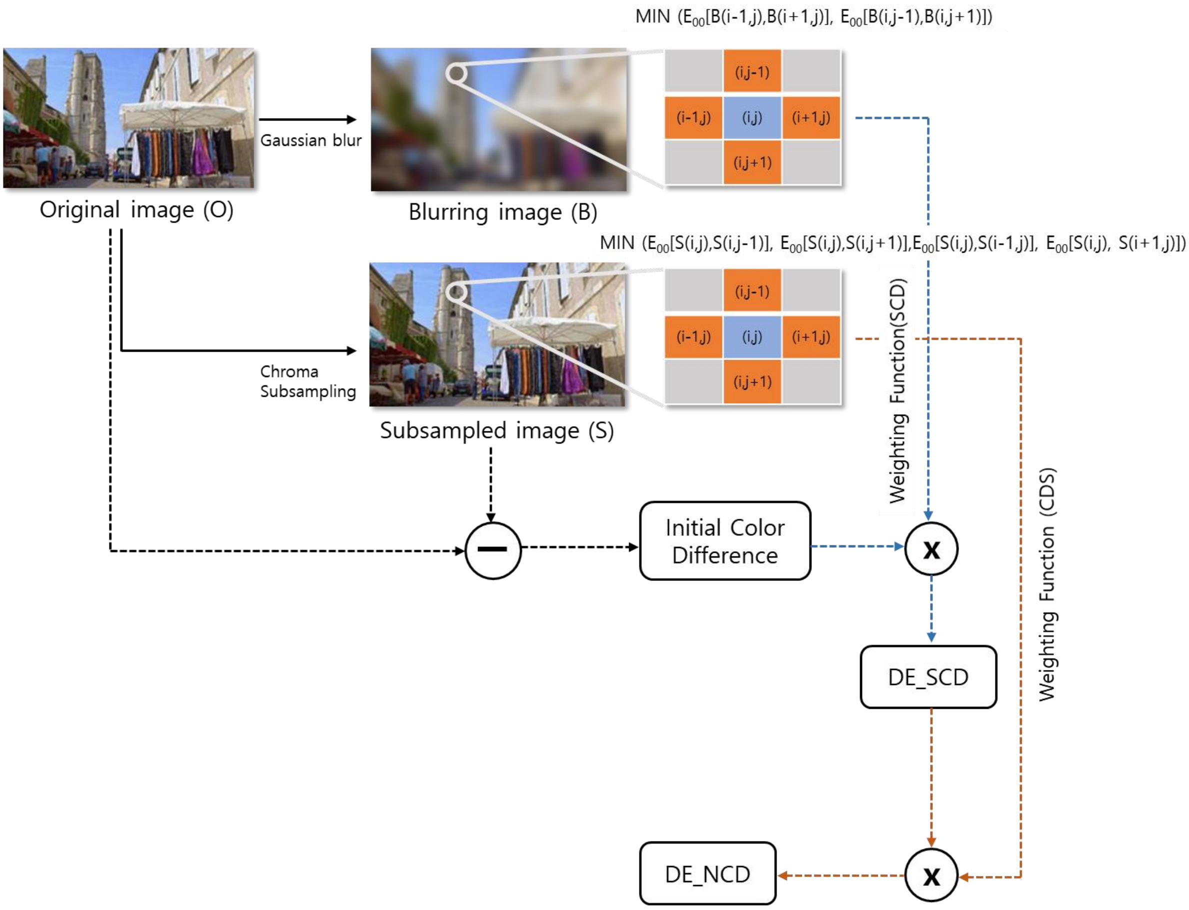


Figure 33 Structure of Chroma subsampling artifact assessment metric

5.5 Chroma Subsampling Artifact Assessment Metric Performance Test

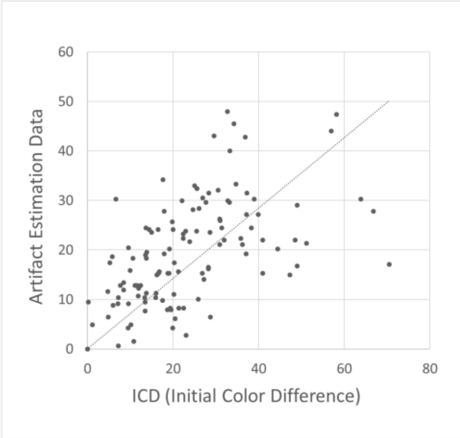
5.5.1 Performance Test with Experimental Data

The correlation is the highest when the final condition was applied for the Initial Color Difference. It seems not that different, however, the effect of metric appears more in the image. Figure 38 shows the image which is compared with color difference metric.

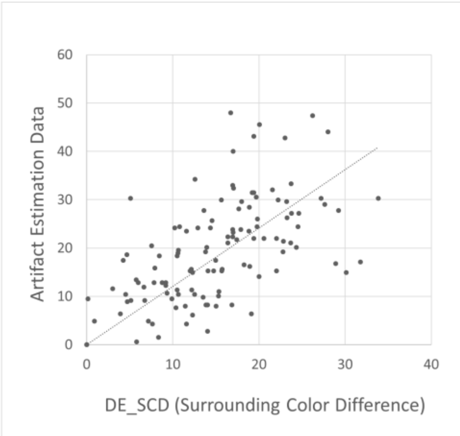
Table 12 Correlation between visual data and final metric

	CORRELATION BETWEEN VISUAL DATA AND FINAL METRIC		
	Initial Color Difference	Surrounding Colors	Neighboring Colors
R VALUE	**0.559**	**0.585**	**0.620**

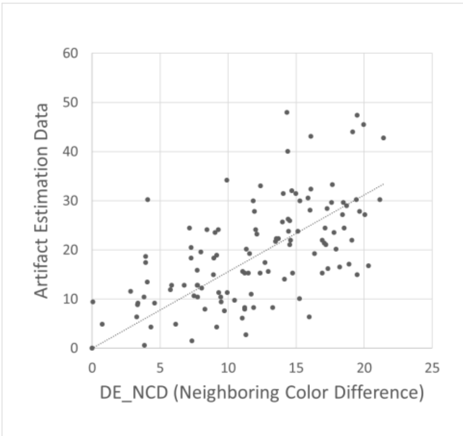
Figure 40 shows the optimized result which represents the difference between perception data and metric applied data. Each graph means that the step of applied conditions. (a) is the first color difference between the original image and subsampled image (ICD) and (b) is data which is applied for surrounding colors condition. (c) is the final metric DE_NCD. The data is gathering on the zero if perception data and the actual value of stimulus is similar.



(a)



(b)



(c)

Figure 40 Perception data of each modeling steps (a) Initial Color Difference (b) Applied Surrounding Colors Effect (c) Applied Neighboring Color Effect

5.5.2 Performance Test with Subjective Evaluation

Figure 41 shows the example of an image that applied the assessment metric. The example image was made with a mosaic pattern that has a well-defined edge of the color. (a) is the original image and (b) is the subsampled image. Below images are expressed artifact error which is assessed by each metric. (c) is applied to the color difference between (a) and (b). (d) is applied to the assessment metric which is optimized in this chapter. Although the error looks no-artifact in (b) image, the color difference metric shows the artifact error just based on the calculation. However, the (d) metric can show the error which has a larger color difference but looks no-artifact.

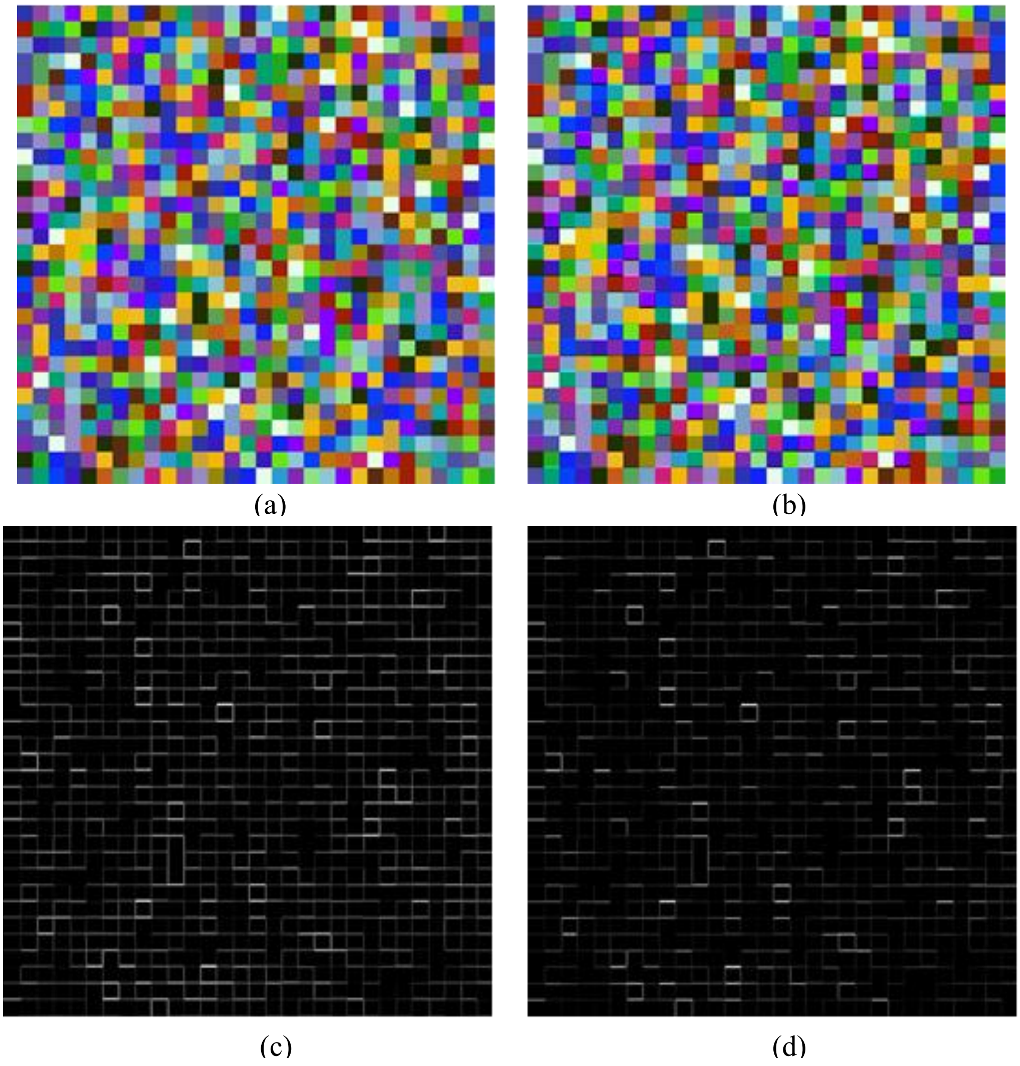


Figure 41 Example of metric applied image (a) original image (b) subsampled image (c) existing metric (dE00) (d) new metric applied image

By using a more simplified mosaic pattern, the metric performance test was conducted. In this test, a total of 10 test stimuli was used and 5 people participated. In one scene, 3 different mosaic patches were shown simultaneously. The color patch is a reference patch which has chroma subsampling artifact and the others show side by side. Participants selected which black and white image shows similar artifacts with the subsampled image. The white line means the magnitude of artifacts. One of the evaluated stimuli shows the color difference between the original image and the subsampled image pixel by pixel. The other is the image which is applied for chroma subsampling artifact assessment metric. The order of the evaluated image was random, so participants selected by using the number 1 or 2. Figure 42 shows the scene of the performance test.

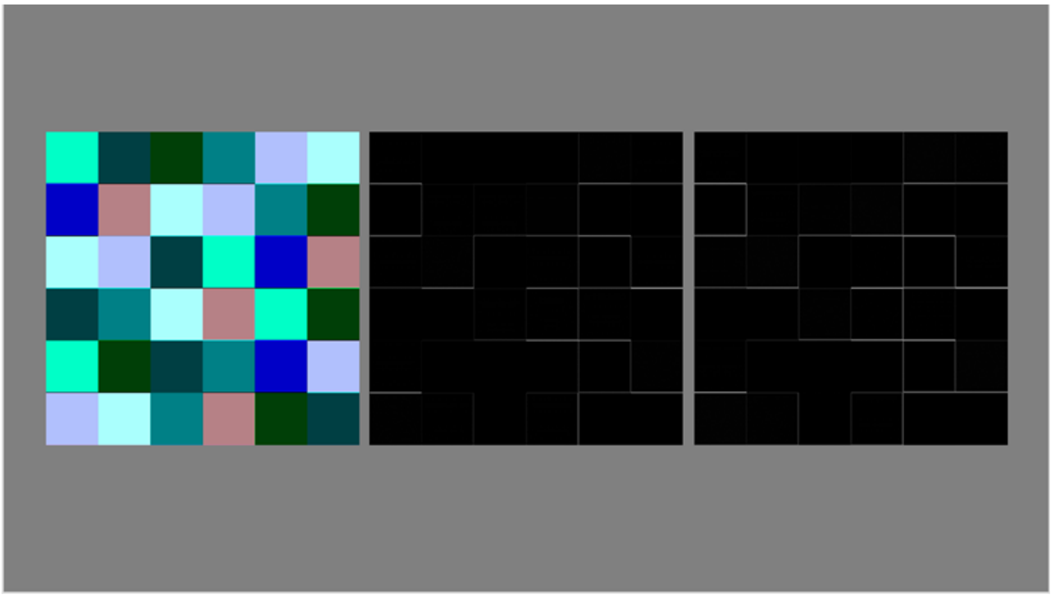


Figure 42 Scene of performance test

Figure 43 shows the performance test result. In this test, there are 50 responses from participants. As a result, 88% of responses indicated that the new metric, which is optimized based on artifact estimation data, is better than the existing method (dE00). According to the result, the new metric which is optimized in this research has better performance.

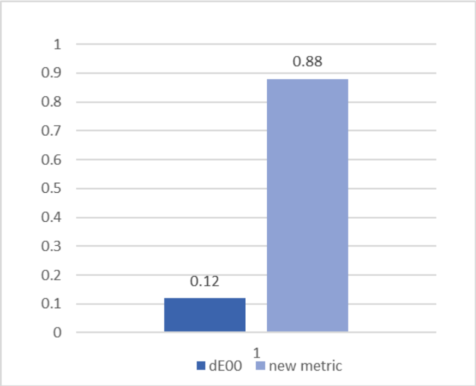


Figure 43 Result of performance test

5.6 Summary

In this chapter, the chroma subsampling artifact assessment metric was modeled. For modeling the metric, the correlation result in chapter 4 was used. With the color difference between the original image and the subsampled image, the surrounding colors effect and neighboring colors effect were used. Those are analyzed with pixels.

1. The color difference between the original image and the subsampled image have the highest correlation with artifact estimation

2. People can't perceive the artifact when the surrounding colors already have large color differences except for artifact error.

3. People can't perceive the artifact well if the artifact color has a similar color with neighboring colors.

By using three findings, the metric was modeling and applied to the images.

The metric performance test was also done. As a result, the new metric which is modeled in this research has better performance than the existing metric (CIEDE00) to evaluate the chroma subsampling artifact.

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6. Conclusion

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The purpose of this research was to investigate the effect factors affecting artifact perception and to model the chroma subsampling artifact assessment metric. A psychophysics experiment was conducted. The stimuli had stripes pattern for maximizing the artifact error simply. Participants evaluated the artifact error with the magnitude estimation method. The reference patch was first shown on the monitor, and then participants evaluate the magnitude of artifact comparing it with the reference patch. If they perceive the artifact error more, they gave the number over 5. If not, they gave the number under 5. A total of 150 stimuli was evaluated and 10 people participated in the experiment.

In the results of the experiment, 4 effect factors of artifact estimation are found.

1) The color difference between original color and subsampled artifact color

The difference of various color components between original color and chroma subsampled color was analyzed to determine which color components most affect artifact estimation. A total of 4 different color components were used: Luminance, chroma, hue, and color difference. As a result, the color difference between original color and chroma subsampled color has the highest correlation comparing with artifact estimation data.

2) The surrounding colors effect

The surrounding colors are the wider range of colors which is located nearby artifact colors. According to the result, as the color difference of surrounding colors increase, the ability to perceive the artifact decreases.

3) The neighboring colors effect

The neighboring colors are the nearest color from artifact colors in this experiment. When the artifact colors are similar with one of the neighboring colors, it is perceived as a part of the neighboring color, meaning that people cannot perceive that artifact well.

4) The effect of the pixel structure

In the experiment, participants perceive the artifact, although the stimuli have no artifact. This misperception occurs because of the RGB subpixel structure of the LCD monitor. When there is a significant difference between R and B channels on the edge of the color, a pixel can be perceived as a GBR subpixel structure, so the intended artifact was estimated. However, this effect was not considered in assessment metric modeling because it varies depending on the display pixel structure.

Using those effect factors, the modeling of the error assessment metric was taken. In metric modeling, the pattern image and the perception data were used firstly. The blurred image was used for applying surrounding colors and the subsampled image was used for weighting function of neighboring colors. The final model can be expressed by the following equations:

$$ICD = E_{00}[O(i,j),S(i,j)]$$

$$SCD = \text{Min}\ (E_{00}[B(i\text{-}1,j),B(i+1,j)],\ E_{00}[B(i,j\text{-}1),B(i,j+1)])$$

$$DE_{SCD} = ICD * \left(\left(\frac{-0.5304 * SCD}{100}\right)^{1.3914} + 0.9294\right)$$

$$NCD = \text{MIN}\ (E_{00}[S(i,j),S(i,j\text{-}1)],\ E_{00}[S(i,j),S(i,j+1)], E_{00}[S(i,j),S(i\text{-}1,j)],\ E_{00}[S(i,j),\ S(i+1,j)])$$

$$DE_{NCD} = DE_{SCD} * \frac{1}{1+e^{-(1.352345*NCD)}}$$

Where ICD means Initial Color Difference, namely that between the original image (O) and the subsampled one (S). The Surrounding Color Difference (SCD) is the second step of the metric. The minimum value of color difference between surrounding colors is the weighting function of the second step. When calculating the SCD, the blurring image was used. The final step for the metric is NCD, the minimum value of artifact pixel and neighboring pixel. NCD value is also the weighting function of the final step. DE_{NCD} is the final metric.

The performance test of the new metric was conducted with a mosaic pattern. In the performance test, the 5 participants selected the better metric 10 times. Eighty-eight percent of respondents selected the new metric modelled in this research, which has a better performance than the existing metric (dE00).

In further studies, this metric will be able to use for developing encoding color signals to decreasing the chroma subsampling error.

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APPENDIX

R,G,B value of test stimuli

color1			sub1			sub2			color2		
R	G	B	R	G	B	R	G	B	R	G	B
0	63	66	53	50	86	128	121	208	184	60	255
26	192	200	118	190	116	41	66	40	58	63	7
246	66	16	180	119	84	241	205	144	101	255	255
184	14	133	131	87	108	210	140	172	0	192	134
111	192	200	143	189	171	201	255	239	237	255	201
0	255	135	141	242	145	121	208	125	177	193	134
247	9	255	174	137	170	241	198	246	0	255	135
0	63	66	0	60	86	0	143	207	0	126	255
99	255	201	0	244	255	0	87	123	0	60	200
183	64	66	184	66	44	182	65	43	183	65	12
181	128	133	203	105	183	223	115	201	246	61	255
171	255	201	197	250	224	106	133	120	118	128	133
0	63	7	52	53	36	171	176	121	245	128	200
0	255	201	0	255	123	0	190	90	0	193	20
0	255	201	0	255	230	0	64	58	0	63	66
122	11	7	111	28	53	200	52	97	184	7	200
246	66	16	196	101	141	76	39	54	61	0	133
177	193	22	139	203	43	169	247	51	98	255	70
247	17	200	209	96	166	244	140	247	242	193	200
111	192	200	191	163	233	95	82	116	121	63	133
237	255	201	237	255	139	234	255	136	237	255	71
62	0	200	100	54	79	88	47	70	122	11	7
237	255	71	162	255	52	105	181	37	0	193	20
245	129	67	174	165	84	232	220	111	0	255	135
121	64	9	111	69	45	200	124	81	181	128	133
122	61	200	90	57	243	19	9	54	6	0	65
12	0	133	0	49	57	0	253	255	98	255	70
122	11	7	90	53	7	242	186	35	98	255	27

119	126	255	103	158	132	161	251	209	170	255	28
59	62	133	60	76	65	203	255	221	237	255	30
245	129	134	246	101	90	54	18	15	60	5	4
0	126	255	0	136	231	0	183	255	31	191	255
124	0	255	92	72	235	120	92	255	53	126	255
178	192	255	230	146	255	102	66	155	123	0	200
59	62	133	60	75	72	153	191	182	177	193	68
183	64	66	192	49	86	117	29	52	122	10	66
171	255	255	122	255	180	82	184	121	21	193	68
170	255	28	161	251	209	103	158	132	119	126	255
53	126	255	73	140	202	127	250	255	171	255	255
237	255	71	182	255	171	173	255	164	101	255	255
98	255	70	157	240	125	192	255	151	237	255	201
242	194	69	185	223	100	193	233	105	98	255	135
122	11	7	100	56	8	161	98	30	117	128	15
0	0	65	31	19	25	172	133	157	246	66	15
58	63	7	51	67	7	194	249	91	170	255	70
117	127	255	167	131	185	193	153	214	245	129	133
48	127	200	0	139	177	21	181	228	0	192	200
0	192	200	0	186	225	0	200	241	0	192	255
0	63	7	0	61	38	91	255	198	98	255	255
177	193	134	219	167	137	211	160	131	245	129	133
0	255	201	0	232	255	0	112	171	0	0	255
0	0	199	0	77	143	0	226	255	0	255	255
122	11	7	118	10	56	246	69	132	247	17	200
0	62	200	0	85	168	0	172	255	0	192	255
246	66	67	189	123	155	96	58	76	58	63	133
0	127	255	142	105	212	172	129	255	246	65	200
0	193	134	82	161	218	67	136	185	121	61	255
121	63	133	106	83	117	138	110	153	117	128	133
110	193	200	186	173	133	92	83	60	121	64	9
48	127	200	0	149	138	20	243	226	0	255	135
245	129	67	182	174	114	229	220	146	98	255	201
0	255	255	88	218	255	15	80	147	60	0	200

122	5	133	98	53	141	87	45	125	58	63	133
0	255	255	0	224	255	0	117	201	57	61	255
18	192	200	49	190	198	79	255	255	98	255	255
110	193	200	188	146	231	192	149	237	246	64	255
246	66	15	199	123	97	241	212	172	237	255	255
0	255	201	130	236	210	166	255	255	237	255	255
110	193	134	167	160	182	195	187	213	245	128	255
183	63	200	122	144	122	176	207	178	0	255	27
0	193	68	61	185	64	69	202	72	110	193	68
48	128	14	64	111	125	78	132	148	122	0	255
58	63	7	43	68	23	80	121	54	48	128	66
0	63	7	0	62	39	0	134	93	0	128	133
181	128	255	198	120	252	226	139	255	245	128	255
117	128	67	80	129	149	9	27	33	0	0	65
47	127	255	0	152	218	0	117	170	0	128	133
242	194	24	167	212	213	18	27	26	0	0	65
48	128	14	96	114	13	189	223	51	242	194	24
122	199	206	123	201	178	65	137	112	66	140	84
131	79	255	158	78	204	217	142	255	244	140	206
244	141	20	169	152	128	200	187	163	121	198	255
51	198	206	51	198	206	51	198	206	51	198	206
246	82	145	178	100	165	142	62	125	73	80	145
133	0	255	0	76	79	125	203	211	0	255	27
189	14	145	189	14	145	189	14	145	189	14	145
65	139	255	78	153	97	164	246	194	176	255	29
0	255	207	160	208	246	89	131	166	246	82	206
0	199	85	62	171	178	0	107	112	73	79	206
237	255	30	239	242	159	57	111	12	77	3	83
73	79	206	57	95	98	84	125	129	66	140	15
73	79	206	79	87	120	122	133	169	128	140	84
0	255	87	87	233	62	140	255	112	237	255	87
186	140	206	119	163	169	130	175	182	51	199	146
241	199	255	124	237	216	109	220	199	0	255	146
66	140	84	116	127	72	139	153	97	186	140	85

0	255	87	60	246	163	91	255	190	112	255	255
189	7	206	166	69	212	211	74	255	188	80	255
247	22	84	160	52	54	243	170	176	182	199	146
66	139	206	47	157	72	129	242	159	112	255	28
73	79	255	101	78	204	104	82	208	132	81	145
182	199	206	204	190	229	220	207	246	241	199	255
237	255	207	167	255	198	68	178	93	0	199	85
0	199	85	0	194	141	0	203	150	0	198	206
128	140	16	169	121	95	204	159	134	244	140	206
112	255	87	151	231	255	0	49	81	0	0	255
51	198	206	107	184	222	96	95	129	73	80	145
0	0	206	0	43	4	187	237	216	176	255	29
128	140	145	102	144	180	94	135	171	66	139	206
0	78	255	0	98	195	93	239	255	0	255	255
0	255	146	160	208	185	35	72	45	189	16	84
133	5	145	133	12	144	244	140	255	244	140	255
0	140	84	0	135	141	55	203	211	50	198	255
246	83	16	129	110	84	130	111	84	0	139	145
0	0	145	107	0	147	158	48	204	247	16	206
189	0	255	91	68	101	169	152	189	52	199	21
66	140	15	88	129	73	0	89	9	0	0	0
112	255	147	155	235	255	31	103	138	73	79	255
188	82	84	96	105	110	159	173	180	51	198	206

L*a*b* data of stimuli

color1			sub1			sub2			color2		
L	a	b	L	a	b	L	a	b	L	a	b
22.9	-17	-5.2	22	12.6	-20	55.9	23.9	-38	53.8	79.4	-72
71.3	-34	-10	71.7	-32	33.9	25.1	-15	16.1	25.1	-7.8	33.7
56.7	70.1	68.6	57	24.4	33.1	85	10.3	39.1	93.1	-34	-11
42.6	71.5	-16	43.4	24.3	-0.5	67.2	34.4	-0.7	69.1	-55	20.7
73.7	-20	-6.5	73.8	-14	8.88	97	-16	9.29	98.6	-9.5	29.9
88.5	-76	46.1	87.9	-41	41	77	-37	36.5	76.5	-9.6	32
60.3	98.2	-61	62.8	22.7	-6.5	85.5	26.4	-10	89	-72	46.8
22.9	-17	-5.2	22.5	-6.8	-20	56.3	-13	-37	54.9	19.5	-71
91.7	-49	19.3	87.4	-42	-20	34.5	-8.9	-25	32.2	38.5	-72
45.7	52.1	29.6	45.8	51.1	43.4	45.1	50.5	42.9	45.2	50.3	56.6
60.4	24.8	9.99	59.5	50.9	-18	64.7	54.6	-20	63	90.4	-57
94.5	-31	23.7	94.2	-15	12.1	54.2	-9.5	7.5	54	0.33	-0.1
21.6	-31	29.2	21.1	-2.4	13.8	71.5	-5.4	31.7	69.9	55.2	-11
89.5	-64	15.9	88.4	-78	51.1	67.7	-63	41.4	67.9	-70	67.3
89.5	-64	15.9	89.3	-56	1.45	23	-21	0.53	22.9	-17	-5.2
25.8	48.3	38.4	25.5	42.3	8.98	47.5	64.1	13.5	45.9	79.6	-49
56.7	70.1	68.6	56.2	45.4	0.09	20.6	23.4	0.04	18.5	50.3	-56
75.5	-17	76.4	75.8	-36	70.7	89.7	-42	82	90.1	-66	75.5
57.2	90.4	-30	58	55.2	-11	73.6	55.7	-29	83.3	22.6	8.62
73.7	-20	-6.5	72.6	25.4	-24	37.9	15.1	-14	37.2	39.5	-25
98.6	-9.5	29.9	97.8	-16	58	97.1	-17	58.3	97.3	-20	84.7
26.5	65.4	-81	29.5	27.7	-3.8	25.4	25.3	-3.5	25.8	48.3	38.4
97.3	-20	84.7	92.6	-48	84.3	67.4	-40	64.2	67.9	-70	67.3
67.5	43.6	56.5	68.1	-2.4	46.6	87.3	-2.8	57.9	88.5	-76	46.1
34.2	25.7	44.7	34.1	19.4	26.4	60.6	29.8	39.9	60.4	24.8	9.99
41	53.9	-57	40	60.3	-82	3.41	16.7	-27	3.19	22.2	-36
13.4	47.9	-65	16.8	-12	-8.1	89.7	-46	-16	90.1	-66	75.5
25.8	48.3	38.4	26	17	36.2	79.5	13.9	79.6	89.9	-68	85.9
59.4	33.8	-63	61.8	-20	11.6	92.2	-29	16.6	92.9	-46	89.5
29.4	20.5	-38	30.7	-7.1	6.97	96.6	-18	17.2	97.1	-22	94.5

68.4	47.9	22.3	62.5	58.2	38.7	9.1	22.1	11.6	9.13	29.1	14.4
54.9	19.5	-71	55.7	1.27	-50	70.8	-12	-45	73.5	-14	-41
41.3	83.4	-93	42.6	50.9	-74	51.6	53.2	-76	55.9	23	-69
79.8	13.9	-31	74.1	52.3	-39	36.6	36.1	-40	35.2	70.7	-67
29.4	20.5	-38	30.7	-5	2.64	75.2	-9.9	5.2	75.7	-16	62.6
45.7	52.1	29.6	45.4	61.9	17	27	43.6	12.1	26.8	51.1	2.33
96	-19	-6.4	92.1	-47	29.7	68.4	-40	26.6	68.9	-60	53.4
92.9	-46	89.5	92.2	-29	16.6	61.8	-20	11.6	59.4	33.8	-63
55.9	23	-69	57.2	-2.4	-33	92	-26	-13	96	-19	-6.4
97.3	-20	84.7	94.7	-32	38.1	93.6	-35	39.9	93.1	-34	-11
90.1	-66	75.5	87.7	-38	50.5	95	-31	47.9	98.7	-9.6	30
81.6	10.9	70.3	84.6	-23	58.7	87.7	-24	60.2	90.7	-60	49.3
25.8	48.3	38.4	28.8	20.2	39.3	48.7	24.8	51.8	52.2	-13	57
3.12	21.9	-36	4.96	8.52	-0.8	61	22.1	-2.1	56.8	70.1	68.6
25.1	-7.8	33.7	25.7	-14	34.1	91.9	-31	70.9	93.1	-45	79.3
59.5	32.7	-63	61	25.8	-17	69.8	28.1	-19	68.4	47.8	22.4
52.4	-0.7	-39	54.3	-18	-24	68.9	-22	-28	70.7	-39	-11
70.7	-39	-11	69.8	-29	-25	74.3	-31	-26	73	-18	-42
21.6	-31	29.2	21.2	-26	11.9	91.4	-51	20.3	93.2	-35	-11
76.5	-9.8	32	73.7	19.9	27.5	71.3	19.5	26.9	68.4	47.8	22.4
90	-61	16.7	84	-37	-25	45	-6.8	-36	32.3	79.2	-108
23.1	64.1	-87	32.2	4.71	-40	82.4	-35	-27	91.1	-48	-14
25.8	48.3	38.4	25.5	49.2	7.47	58.7	73.7	9.59	57.2	90.4	-30
32.3	37.2	-72	36.4	9.4	-48	67.5	-7.8	-50	73	-18	-42
57.1	71.2	45.8	60.5	33.4	-1.6	29.7	23.2	-1.1	29.5	19.9	-38
55	18.2	-70	53.3	38.1	-44	64	42.4	-49	60.3	81.2	-26
69.1	-56	20.8	64.4	-7.4	-30	55.1	-6.6	-27	46	68.4	-85
37.2	39	-25	39.5	18.8	-12	51.7	21.7	-14	54	-0	-0
73.8	-20	-6.5	71.9	3.66	26.5	36.2	2.66	18.2	34.2	25.7	44.7
52.4	-0.7	-39	56.1	-36	-0.2	86.6	-47	-0.2	89	-73	46.8
67.5	43.6	56.6	71.6	-0.7	36.1	87.6	-0.9	41.4	91.7	-49	19.3
91.6	-45	-13	82.1	-20	-28	33.9	6.3	-40	26.3	65.3	-82
30	59.3	-37	32.2	39.8	-38	27.6	37.6	-36	29.5	19.9	-38
91.1	-48	-14	82.4	-30	-27	48.3	0.32	-47	40.7	61.5	-94

71.4	-34	-10	71.1	-32	-9.6	92.7	-38	-12	93.2	-35	-11
73.8	-20	-6.5	68.3	33.2	-30	69.8	33.7	-30	63.3	89.7	-56
56.8	70.1	68.6	60.5	31	30.8	87.1	9.69	28	100	-0	-0
89.6	-64	16	86.7	-32	8.03	95.6	-22	-2.1	100	-0	-0
72.3	-33	25.7	68.1	10.2	-5.1	78.3	11.2	-5.6	72.3	64.5	-42
50.1	66.9	-42	58.5	-8.4	13	81	-10	16.1	87.7	-86	83.2
68.2	-66	52.4	67.1	-52	53.3	72.6	-55	56	71.5	-41	56.9
47.9	-41	51.8	44.9	-11	-9.6	52.9	-12	-11	41	83.3	-93
25.1	-7.8	33.7	25.9	-18	28.3	47.3	-24	35.9	48.3	-36	29.9
21.6	-31	29.2	21.7	-26	11.8	49.8	-41	16.1	48.6	-29	-8.5
65.1	47.9	-54	64.7	53.2	-46	72.2	54.4	-42	72.3	64.5	-42
52.6	-10	36.1	52.1	-9.4	-12	6.05	-3.8	-6.1	3.12	21.9	-36
56	21.7	-69	59.8	-12	-37	46.6	-9.9	-32	48.6	-29	-8.5
81.4	9.66	83.3	82.5	-10	0.3	6.05	-3.2	0.09	3.12	21.9	-36
47.9	-41	51.8	45.9	-16	51.5	84.4	-25	77.7	81.4	9.66	83.3
76.2	-18	-6	76.2	-25	8.52	53	-27	10	53.2	-33	26.3
50.2	61.8	-78	49.2	54.8	-46	71.8	50.6	-43	72.4	50	-10
69.6	36.5	75.6	65.1	6.43	19.6	77.3	5.88	18.6	78	-3.9	-34
73.7	-33	-9.9	73.7	-33	-9.9	73.7	-33	-9.9	73.7	-33	-9.9
60.7	69.9	4.99	54.3	43.2	-17	40	45.2	-16	36.7	16.3	-34
42.5	84.2	-91	28.4	-20	-5.9	77.7	-18	-6	87.7	-86	83.2
44.1	73.9	-21	44.1	73.9	-21	44.1	73.9	-21	44.1	73.9	-21
59.8	17	-63	58.1	-32	25.5	90.7	-29	21.8	93.2	-44	89.9
89.7	-63	13.2	81.8	-3.5	-17	53.8	-3.2	-19	62.6	76.2	-25
70.2	-66	46.7	65	-27	-8.2	41.1	-26	-7.5	40.5	34.8	-62
97.1	-22	94.5	94	-6.3	43.5	42.2	-31	47.4	17	42.5	-26
40.5	34.8	-62	38.3	-11	-3.4	50.5	-11	-3.3	52.6	-39	55.8
40.5	34.8	-62	38	7.21	-17	57	6.24	-15	57.2	-9.3	32.2
88	-83	66.4	82.4	-61	70.4	91.9	-51	61.4	97.4	-20	79
65.8	31.3	-21	65	-10	-3.4	69.6	-10	-3.3	72.3	-46	19.1
86.5	29.5	-20	87	-32	5.43	81.4	-33	5.68	88.7	-75	40.7
53.2	-33	26.3	52.3	-9.5	32.9	62	-9.5	31.4	63	15.4	40.5
88.8	-76	67.6	86.5	-58	30.1	91.3	-52	24	93.6	-33	-10
47.1	81.2	-50	49.2	62.4	-51	59	78.4	-60	57.1	72.5	-67

53.9	81.8	31.4	39.3	49	28.7	77.7	31.5	12.7	78.7	-9	28.9
56.8	-2.3	-36	57.9	-46	38.9	87.4	-43	33.8	90.4	-64	86.4
45.2	53.3	-86	42.3	41.1	-58	43.9	40.7	-57	43.2	34.9	-23
79.9	0	-0	80.1	15.2	-11	86	14.9	-10	86.5	29.5	-20
98.8	-8.9	27.3	94.4	-32	24.7	65.4	-45	37.2	70.2	-66	46.7
70.2	-66	46.7	69.7	-55	17.9	73	-52	18.1	72.6	-40	-12
56.7	-14	60.7	56.4	19.3	26.1	70.4	17.5	24	72.4	50	-10
90.7	-61	70	87.9	-12	-19	18	-0.8	-23	32.3	79.2	-108
73.7	-33	-9.9	71.8	-12	-20	42.4	10.5	-15	36.7	16.3	-34
23.9	65.5	-89	12.5	-24	18	90.3	-15	10.7	93.2	-44	89.9
58.5	0	-0	58.9	-3.3	-19	55.7	-3.2	-19	56.8	-2.3	-36
42.7	48.7	-90	42.3	10.3	-53	87.9	-28	-19	91.9	-43	-13
88.7	-75	40.7	80.3	-15	10.9	26.9	-19	15.3	42.2	68.7	13.9
33	63.1	-39	33.1	62.4	-39	74.4	59	-39	74.5	58.9	-39
51.3	-47	23.4	51.2	-30	-8.9	75.2	-33	-10	75.7	-16	-38
59	63.9	69.6	48.7	7.31	21.5	49	7.28	21.4	52.8	-31	-9.1
15	50.9	-69	28	59	-49	44.5	67.7	-54	57.4	91.1	-33
51	90.3	-76	32.7	19.2	-13	66.5	16	-11	71	-61	70.2
52.6	-39	55.8	50.8	-22	29.5	32.1	-40	38.6	0	0	0
91.3	-55	44.6	89.2	-13	-17	41.5	-9.7	-22	45.2	53.3	-86
49.9	47.1	24.3	44.8	0	-0	71	0	-0	73.7	-33	-9.9

dE data

dE00 (c1-s1)	dE00 (s1-s2)	dE00 (c1-s2)	dE00 (c2-s1)	dE00 (c2-s2)
26.894942	30.563972	39.247497	34.663669	16.436102
25.058799	47.241355	50.101513	48.211709	11.582742
15.076933	24.206943	32.883895	50.936129	38.234214
15.932535	22.916292	26.425961	61.25137	63.864713
11.864163	15.228416	19.286907	20.847879	13.491725
9.873499	7.563782	13.554362	16.681244	13.593725
23.112598	16.975401	28.210354	65.29086	66.818703
13.48344	30.527742	34.129042	29.581216	12.391785
23.064435	48.710756	58.750054	60.740787	14.141668
7.1582099	0.6731109	7.1206023	6.119872	6.1307611
17.947674	4.5953705	19.071378	13.303806	12.176229
8.5542848	29.847984	32.386308	34.227246	12.444952
17.313026	49.523793	50.804714	60.182768	48.99723
11.833658	15.071195	18.383374	15.648065	7.1972913
7.160206	63.098251	63.890474	63.905633	4.8825145
15.048763	19.55705	24.2313	28.372325	22.347807
28.195839	31.912237	41.98059	39.225883	23.410488
9.5280619	9.7119997	14.01133	13.410762	8.8393706
9.5379094	14.797973	15.927876	25.443192	22.367996
30.546323	33.39578	45.957516	34.152544	11.075455
9.4684915	0.541393	9.617258	6.4121776	6.3427432
26.076539	3.2457954	26.247142	22.359648	22.174541
11.940261	17.999211	23.67706	19.631278	8.9892803
27.311899	14.04241	31.878499	33.541095	31.349461
7.2875276	26.636351	26.25431	28.559375	16.240588
6.6490399	30.834252	29.980779	29.180769	3.9817258
21.385263	72.465532	86.530869	79.460181	35.807032
16.579995	54.455714	60.939858	71.893419	37.211853
40.966925	22.179287	50.433973	32.526956	21.912693
30.909077	55.850695	68.748301	61.707141	23.88668

8.3915138	46.763248	52.242761	45.978578	3.4226859
5.935547	14.620961	18.752229	16.836006	2.5895171
8.2830127	8.8438975	12.504983	19.196906	14.936411
17.584168	35.911346	40.313102	37.854337	10.153666
26.769966	43.784318	54.185005	50.343923	23.564071
8.3918206	16.364136	17.864765	17.181474	6.1353176
22.414084	16.547991	27.924768	17.674106	9.1548094
21.912693	22.179287	32.526956	50.433973	40.966925
7.0716965	31.404517	38.756857	33.604067	5.4785775
17.311876	1.3431407	17.646854	26.920171	27.19268
8.4364982	5.2042875	10.892739	14.768995	11.075289
21.1795	2.08356	21.622603	16.092452	15.708044
15.605771	17.717204	25.85472	32.066102	25.482473
19.508774	46.019072	49.740693	50.201126	29.570258
4.0928788	60.29352	61.550033	61.498594	4.7120005
17.97578	7.3252941	19.665484	23.430399	22.886682
12.151031	12.74485	19.339865	19.399838	13.702623
9.9417134	3.491544	10.323296	9.7414756	9.5666196
8.3966062	65.858643	65.287803	67.775995	18.680173
23.920557	1.8630465	23.984636	16.34543	16.006854
25.913243	36.105861	51.791083	59.502777	25.691819
19.889248	50.58814	68.406922	57.855426	11.524782
16.627655	30.761432	35.441607	32.976797	14.40973
10.143441	32.649511	41.045607	38.463554	7.2566175
22.091577	29.536437	34.280281	37.024076	21.046736
19.819884	9.7530178	22.573535	19.07487	18.271295
37.123089	8.2682456	38.026387	28.912662	23.27161
9.6610798	11.739786	15.682834	22.82212	19.527855
28.334806	34.556497	44.099783	39.389529	15.861559
28.717445	23.586512	40.556089	31.948318	19.2041
25.310761	11.287143	29.337274	30.906109	28.618187
16.328365	46.445542	56.449728	60.847515	20.502556
7.7483325	3.6921344	8.0905085	10.918795	10.595328
12.685887	33.229454	42.89212	48.134464	21.331924

1.1378743	14.861935	14.540592	15.000803	1.1230248
30.839803	1.1221894	30.693692	15.349478	15.532368
13.412861	23.794098	32.848153	35.878093	19.949425
10.634417	9.5976473	16.969875	23.686742	19.084067
39.876388	7.672134	41.0329	22.256099	21.887502
51.198929	17.57638	59.77385	34.023003	25.21817
4.4379676	4.3879654	5.2530671	5.8704003	5.2114072
33.287848	7.9942382	34.079154	19.38357	22.9713
7.7048944	18.375773	20.814129	20.860225	7.2706454
8.4332928	24.099148	24.852169	26.210916	16.015862
4.8266724	6.1962672	8.6362186	7.7000991	3.2824111
31.015153	35.853596	44.523983	40.456115	14.461979
13.483081	12.977588	14.429462	21.45244	17.943879
32.66575	72.019033	76.20065	77.44508	23.268358
11.995883	32.340244	32.215791	34.635985	19.13109
10.830394	19.221383	22.591234	21.031406	8.1788073
9.6527084	19.789271	21.266652	24.721981	13.733859
19.582597	9.3520845	20.589338	35.139729	33.175837
0	0	0	0	0
14.119862	14.009105	24.073037	25.691018	20.301324
34.159799	48.066985	43.604099	62.830399	33.787333
0	0	0	0	0
49.004959	24.074819	52.119407	31.564003	19.91107
31.688973	22.288224	41.986586	37.962693	36.817087
27.27057	23.356619	38.176075	40.07864	31.944518
13.173039	43.216943	45.449415	90.988662	70.445523
26.507981	11.472519	27.813367	30.806773	27.705853
16.280071	18.629289	23.478045	42.01691	36.234112
7.225308	6.7421857	8.4011719	19.843367	16.478946
24.682017	3.6864422	24.708591	21.001662	20.370246
38.981217	3.6817731	39.29971	16.620147	17.061672
14.124956	8.8464273	15.909114	20.945328	18.738954
10.733734	3.8666459	12.948378	22.863955	20.216477
5.7759597	10.112049	12.123236	8.7325934	3.9332339

16.933283	35.527781	24.147662	52.127405	34.701227
47.313026	22.176028	50.847324	26.84751	13.896779
6.7741048	1.4959056	6.3947911	13.685231	13.658768
15.936233	3.9279533	16.244281	9.0543148	8.2159085
13.832826	20.840222	27.933482	19.597139	6.965821
10.201882	2.7151077	10.35162	17.578695	17.493235
28.281347	11.783347	29.94691	31.319946	28.015398
44.408044	68.890759	85.444144	52.254634	20.954427
14.411246	34.630849	38.976035	37.806671	9.4116579
48.492262	77.51202	74.400103	81.684654	24.422152
13.378813	2.955469	13.730471	6.7765903	6.5137909
11.609885	44.119992	47.538135	50.070014	8.4494992
20.866419	51.758798	58.828223	60.625983	56.952876
0.1991837	39.862131	40.002163	39.878951	0.0254573
19.356969	20.19465	28.154544	27.057596	17.703964
25.308726	0.2974165	25.205464	32.822071	32.766615
13.7028	13.952017	25.339741	29.290917	16.738314
28.189079	33.900648	27.871174	72.249676	58.186441
9.5479593	18.319846	19.686385	0	0
37.087839	39.382175	58.180719	39.539652	16.138223
25.612793	23.689723	31.129706	34.144981	22.637554

RGB value of No-artifact stimuli

color1			color2		
R	G	B	R	G	B
246	63	200	124	0	255
178	192	255	171	255	255
62	58	255	122	5	133
124	0	255	16	58	255
170	255	28	18	0	200
246	66	16	16	58	255
0	63	66	247	22	14
20	193	20	24	0	255
247	22	66	49	128	66
0	60	200	20	193	20
0	255	70	170	255	28
0	193	68	242	193	134
0	255	134	242	193	200
0	255	201	184	7	200
110	193	21	0	0	65
0	127	255	237	255	71
0	0	199	181	129	133
121	64	66	121	63	133
0	128	66	237	255	201
18	192	200	48	128	14
244	140	206	237	255	87
247	20	145	0	78	255
182	198	255	0	140	84
133	0	255	52	199	21
189	16	84	0	255	207
0	0	255	189	0	255
189	7	206	0	255	27
246	82	206	74	81	9
246	81	255	244	141	20
237	255	207	247	9	255

Lab value of No-artifact stimuli

color1			color2		
L	a	b	L	a	b
60.1963	81.6274	-25.782	41.3184	83.4234	-92.615
79.7527	13.8586	-30.83	95.9526	-18.781	-6.4141
40.4879	63.1784	-94.175	30.1408	59.3626	-36.551
41.3184	83.4234	-92.615	38.7807	61.0594	-97.057
92.9174	-46.353	89.4522	23.3962	64.1761	-86.745
56.7481	70.0941	68.5835	38.7807	61.0594	-97.057
22.8514	-17.189	-5.1603	53.2331	80.1059	67.1986
68.6701	-63.149	68.202	32.6901	79.3155	-107.21
53.6056	81.1211	41.9434	48.3307	-35.922	29.8508
32.2266	38.5275	-72.076	68.6701	-63.149	68.202
87.9035	-84.028	72.5989	92.917	-46.359	89.4516
68.1798	-66.456	52.4054	82.2261	15.1674	40.5162
88.4977	-76.6	46.1163	83.4185	22.4271	8.75151
90.0257	-60.817	16.7254	45.7447	79.4864	-49.225
71.2406	-43.393	71.3156	3.11585	21.8874	-36.4
54.9899	18.1641	-70.488	97.2783	-20.431	84.7512
23.078	64.0696	-87.266	60.3759	24.5036	10.0285
34.8605	28.9547	13.605	37.2414	39.041	-25.313
47.0335	-46.256	27.9599	98.6714	-9.6307	30.0157
71.358	-34.368	-10.323	47.8999	-40.813	51.7859
72.4255	49.9526	-10.433	97.3745	-19.659	78.9772
55.2505	85.5119	-2.9911	42.7472	48.7336	-90.5
81.6589	11.7021	-27.879	51.3086	-46.96	23.3929
42.5427	84.1835	-90.552	70.9722	-60.874	70.2361
42.1561	68.6976	13.9333	89.6741	-63.034	13.2299
32.3026	79.1936	-107.87	50.9654	90.2578	-76.417
47.106	81.2389	-50.31	88.5597	-78.871	84.1839
62.6012	76.1518	-25.317	32.8851	-9.3161	40.8239
65.16	84.2064	-53.134	69.6215	36.4848	75.5805
98.7736	-8.8681	27.279	60.3199	98.2497	-60.845

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